NUREG/CR-4070
PNL-5300
Vol. 1

Bivalve Fouling of Nuclear Power Plant Service-Water Systems

Correlation of Bivalve Biological Characteristics and Raw-Water System Design

Prepared by D. A. Neitzel, K. I. Johnson, T. L. Page,
J. S. Young, P. M. Daling

Pacific Northwest Laboratory
Operated by
Battelle Memorial Institute

Prepared for
U.S. Nuclear Regulatory
Commission

NOTICE

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, or any of their employees, makes any warranty, expressed or implied, or assumes any legal liability of responsibility for any third party's use, or the results of such use, of any information, apparatus, product or process disclosed in this report, or represents that its use by such third party would not infringe privately owned rights.

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 NRC/GPO Sales Program, U.S. Nuclear Regulatory Commission,
   Washington, DC 20555
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 NRC/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 Technical Information and Document Control, 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.

GPO Printed copy price: $5.50

NUREG/CR-4070
PNL-5300
Vol. 1
RE

Bivalve Fouling of Nuclear Power Plant Service-Water Systems

Correlation of Bivalve Biological Characteristics and Raw-Water System Design

Manuscript Completed: November 1984
Date Published: December 1984

D. A. Neitzel, K. I. Johnson, T. L. Page,
J. S. Young, P. M. Daling

Pacific Northwest Laboratory
Richland, WA 99352

Prepared for
Division of Radiation Programs and Earth Sciences
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555
NRC FIN B2463

PREFACE

The Nuclear Regulatory Commission (NRC), Office of Nuclear Regulatory Research, is compiling information that can be used to develop technical specifications for surveillance of raw-water systems at nuclear power plants. The surveillance is intended to provide an early indication of biofouling problems in the service-related components of these systems. The reports provide data that give NRC staff the required basis for adequately addressing these biofouling problems when they arise at operating facilities and during Office of Licensing safety hearings.

The first report (Volume 1) documents and reviews information about the biological characteristics of bivalve organisms that enhance their ability to infest raw-water and fire protection systems at nuclear power plants and that are relevant to understand the effect of various control and surveillance strategies. Volume 1 also reviews safety-related auxiliary system components, configurations, and operating procedures that present a likely potential for biofouling and the conditions under which this fouling could develop. Recommendations for additional research on fouling are made.

Volume 2 reviews the state of the art of biofouling control and surveillance strategies that have been used at both nuclear and non-nuclear power plants and their effectiveness under various situations and plant system configurations. Recommendations are made for implementing more effective control and surveillance strategies that could be used at nuclear power plants on the basis on current technology and demonstrated effectiveness.

Volume 3 reviews factors that might interact with "normal" levels of plant biofouling and exacerbate non-fouling problems at a nuclear facility. Focus of the volume is on those factors that could lead to a more critical situation than would exist had either the biofouling or the non-fouling problem occurred alone. Topics that are addressed include specific operating procedures, minor seismic events, a system flow surge, a rapid change in system water temperature, and shock chlorination. Specific surveillance and control procedures that might actually increase fouling problems are identified, and the severity of these events in terms of reduced design capability of the system are examined.

ABSTRACT

Fouling of raw-water systems in nuclear power plants in the United States can affect the safe operation of a power plant. This report describes correlations between the biology of bivalve organisms and the design and operation of power plants that allow bivalves to enter and reside in nuclear power plants. Discussions are focused on safety-related raw-water systems subject to fouling by the Asiatic clam (*Corbicula fluminea*), the blue mussel (*Mytilus edulis*), and the American oyster (*Crassostrea virginica*). Score sheets to rate fouling potential of power plant systems and components are provided.

EXECUTIVE SUMMARY

Macroinvertebrate fouling of raw-water systems can affect the safe operation of a nuclear power plant. In a survey of over 150 power plants throughout the United States, NRC staff determined that Asiatic clams, blue mussels, and American oysters were the most common bivalves that caused fouling.

Bivalve larvae and juveniles are free-living for some period after their release from the adult. They are pumped into the system along with the system cooling water. Screen and strainer openings, which range from 4 to 13 mm (3/16 to 1/2 inch), allow Asiatic clam larvae (220 μm by 50 μm), blue mussel larvae (90 μm), and American oyster larvae (90 to 100 μm) to enter the raw-water systems.

The fate of bivalve larvae within the service-water system depends partly on water velocities within the system. Bivalve larvae can move through and grow in an environment with low to moderate water currents. If velocities are too fast to allow settlement, larvae will be flushed through the system. If the currents carry the larvae into a completely stagnant environment, the larvae may eventually die from lack of food and oxygen. Asiatic clams require a flow velocity of less than 0.3 mps (1.0 fps) for juvenile settlement. Blue mussel and American oyster larvae can attach in currents up to 1.2 mps (4.0 fps). Flow velocities in raw-water systems range from stagnant to greater than 1.2 mps.

The extent of bivalve fouling can be correlated with the availability of suitable substrates within the raw-water system. Bivalve growth to maturation occurs after settlement. A raw-water system contains many substrates suitable for settlement. Some of the substrates that favor the settlement of bivalve larvae are corrosion products and silt.

Fouling is a problem when bivalve shells block or redirect flow within a system or component of the raw-water system. Growth of bivalve juveniles to a size that can clog raw-water system components will vary with many environmental factors; however, water temperature may have the greatest influence on bivalve growth in a power plant's raw-water system.

Bivalve growth and survival can be retarded by injecting chemicals into the raw-water system. All power plants either use some antifoulant system or have contingencies for antifoulant systems. Bivalves, however, can avoid antifoulant chemicals. For an antifoulant system to be effective, the system operator must apply methods that overcome bivalve avoidance behavior.

ACKNOWLEDGMENTS

This report was prepared by the Pacific Northwest Laboratory (PNL), operated by Battelle Memorial Institute for the U.S. Department of Energy. The work was performed for the U.S. Nuclear Regulatory Commission, Office of Nuclear Research. The review and preparation of this report were done under the guidance of Frank Swanberg of NRC.

Many individuals shared their experience with biofouling problems and controls. We especially thank the following individuals: Fred Rippe and Tony Eaton of the Washington Public Power Supply System; Gordon Rich of Portland Genral Electric; Bob West of Arkansas Power and Light Company; Joe Johnson and Pam Wilt of the Tennessee Valley Authority; Christopher Benedict of Carolina Power and Light Company; Gary Johnson of Northeastern Utilities; Lew Scotton and Bill Armstrong of Boston Edison Company; John Balletto of Public Service Electric and Gas; and Lew Anastasia of Commonwealth Edison.

Carolynn Novich provided editorial assistance. Ginny Woodcock typed the manuscript.

CONTENTS

FIGURES

TABLES

GLOSSARY

auxiliary cooling system	The raw-water system that serves the turbine generating system or non-nuclear systems.
chloramines	Any class of chlorinated compounds derived from ammonia by replacing one or more hydrogens with an organic group.
circulating-water system	Cooling system that removes heat from the main condensers.
geonegative	A tendency of an organism to move away from gravity.
oocyte	An egg before the first cells divide from the ovum during maturation.
photopositive	A tendency of an organism to move towards a light source.
photonegative	A tendency of an organism to move away from a light source.
plantigrade	Locomotion by use of a foot.
raw-water system	Combined service, auxiliary, and circulating water systems plus that portion of the fire protection system that uses unheated water.
service-water system	The raw-water system that serves the reactor support systems or nuclear systems.

CORRELATION OF BIVALVE BIOLOGICAL CHARACTERISTICS AND RAW-WATER SYSTEM DESIGN

INTRODUCTION

Piping, valves, and other components of raw-water systems that use surface water without extensive treatment can be fouled or clogged by plants and animals. This can be a problem in systems or components that require reliable or uninterrupted flow. Fouling occurs when organisms attach themselves to available substrates or find a suitable area for settlement and growth within the system. Clogging occurs when organisms or parts of organisms are pumped or washed into a pipe, valve, strainer, screen or any other constriction in a quantity that obstructs, diverts, or blocks normal flow. Almost 2000 species of plants and animals have been reported to foul or clog circulating-water systems that use untreated water (WHOI 1952).

During 1981, several biofouling events involving blockages in the raw-water system of safety-related equipment were reported at nuclear power plants. As a result of these events, the Office of Inspection and Enforcement of the Nuclear Regulatory Commission (NRC) issued Bulletin IEB 81-03, which required all licensees of nuclear generation units to assess the potential for fouling of safety related equipment at their facilities. The results of these bulletins were reviewed by M. Masnik of NRC (Masnik, unpublished ms.) and Parameter, Inc. (Parameter 1982). One hundred and fifty-five power plant units were required to respond to IEB 81-03. Seventy-one of the units were operational and 84 were under construction when the bulletin was issued. Asiatic clams, blue mussels and American oysters were the bivalves most cited in the responses. The geographical distribution of these bivalves throughout the United States and the location of nuclear power plants are shown in Figures 1, 2, and 3.

The purpose of this study was to provide information that could be used to develop technical surveillance and control specifications for minimizing biofouling in the safety-related components of raw-water systems. Surveillance would provide an early indication of biofouling problems.

The study was divided into four tasks:

- Document and review the state-of-knowledge about the biological characteristics of fouling organisms which enhance their ability to infest raw-water or fire protection systems at nuclear power plants. Also, identify characteristics that influence the effectiveness of various control and surveillance strategies.
- Identify system components, system configurations, and operating procedures susceptible to biofouling and the conditions under which fouling can develop. Categorize the systems or components according to their potential for fouling and their safety significance.

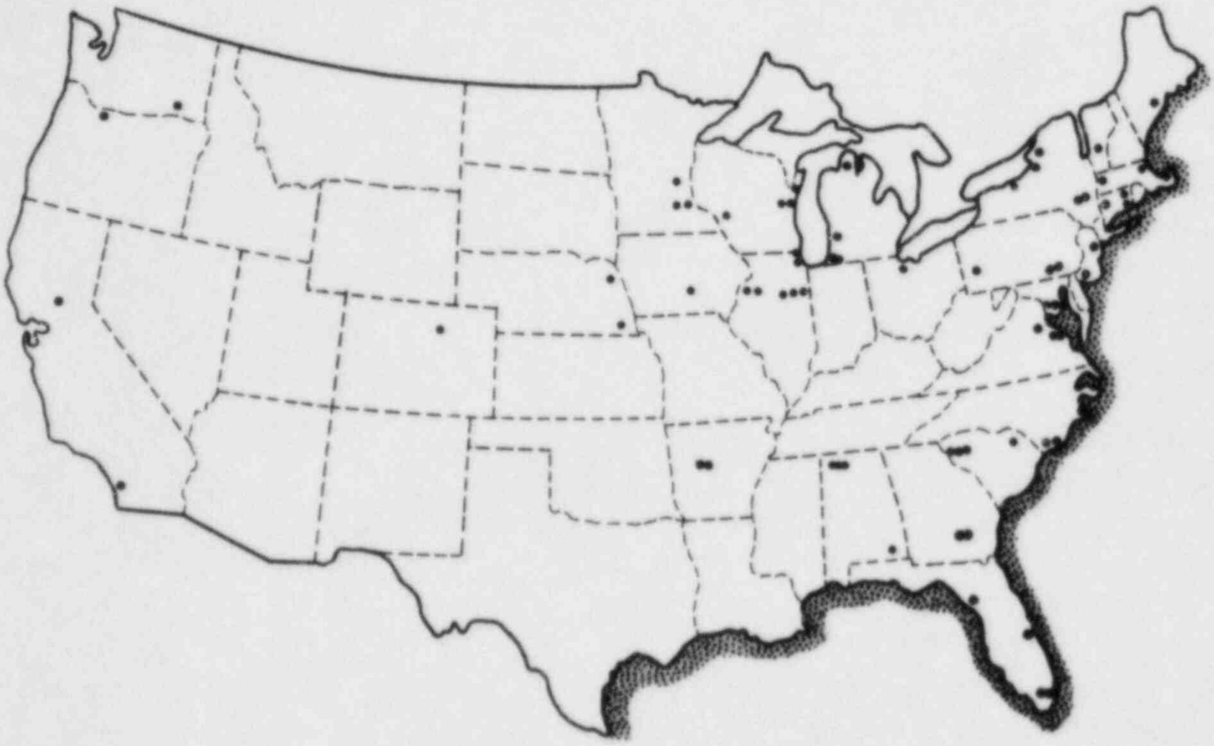

FIGURE 3. Distribution of American Oysters in Relation to Operating Nuclear Power Plants in the United States

- Evaluate biofouling control and surveillance strategies that have been used at both nuclear and non-nuclear power plants and assess their effectiveness under various plant-system configurations.
- Identify factors that might interact with "normal" levels of power plant biofouling to exacerbate fouling problems and lead to a more critical situation than would exist had either the fouling or the incident occurred alone.

This report is organized into five main chapters. Chapter 1 contains a discussion of the safety significance of bivalve fouling of raw-water systems. Chapter 2 contains score sheets that can be used to assess potential bivalve fouling at nuclear power plants. Chapter 3 summarizes correlations between bivalve biology and engineering design. Chapter 4 contains a review of the biological characteristics of bivalves, emphasizing those characteristics that are related to bivalve fouling. Chapter 5 contains a review of the engineering design of raw-water systems and components of nuclear power plants.

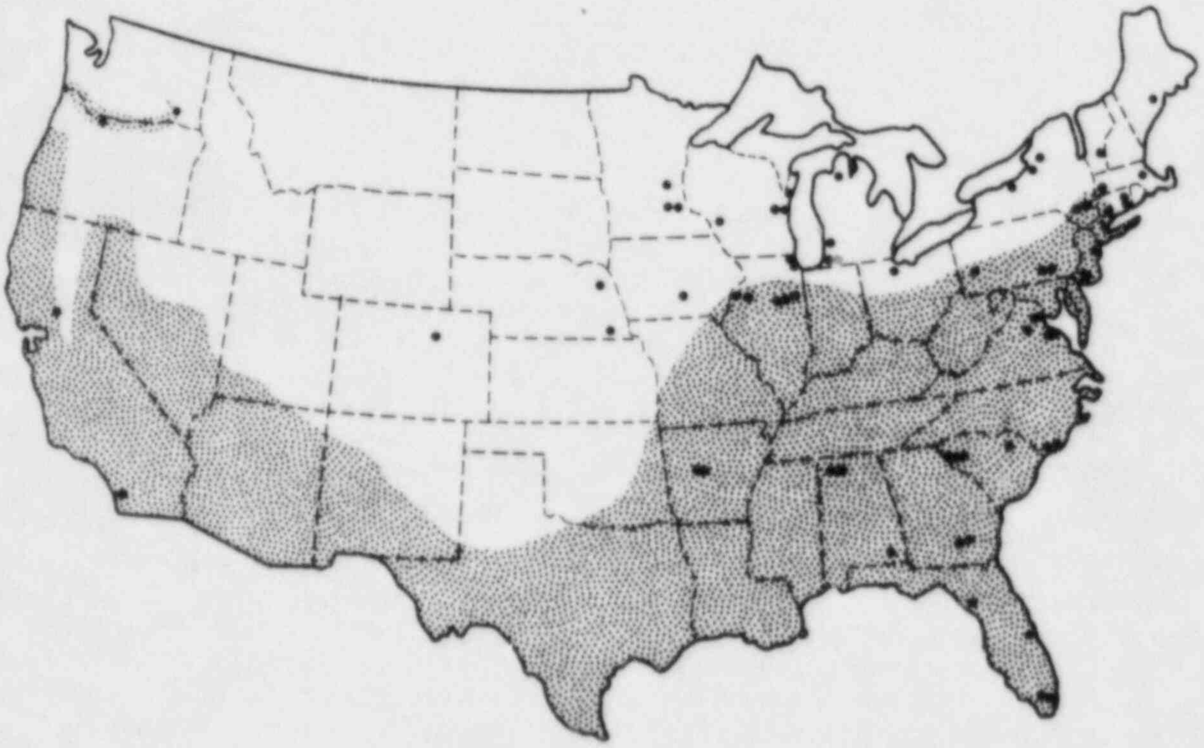

FIGURE 1. Distribution of Asiatic Clams in Relation to Operating Nuclear Power Plants in the United States

FIGURE 2. Distribution of Blue Mussels in Relation to Operating Nuclear Power Plants in the United States

RECOMMENDATIONS

The following recommendations for further research were made as a result of this study:

- The effectiveness of fouling control techniques should be studied. Particular emphasis should be given to the effectiveness of fouling control as it relates to different raw-water systems, bivalve populations, and source water environments.
- The effectiveness of fouling surveillance techniques should be studied. The study should identify those surveillance and control techniques that prevent or restrict bivalves from entering raw-water systems.
- Bivalve fouling should be reviewed as an interactive factor in a potential safety problem. Safety problems can be exacerbated by bivalve fouling, and plant operators should know what conditions could lead to a more critical situation than would exist had either the fouling or the safety problem occurred alone.
- Correlations between the design of raw-water systems and the biological characteristics of bivalves should be quantified more precisely. These data could aid in the control of bivalve fouling of raw-water systems.

The findings of this and other fouling studies should be made readily available to plant operators. The findings could also be used as a basis for the development of effective bivalve surveillance and fouling control programs.

SAFETY SIGNIFICANCE OF BIVALVE FOULING

Bivalve fouling represents a common cause failure mode. This means that bivalve fouling has the potential to affect all raw-water systems, including the backup cooling loops provided for the safety-related cooling systems. Two examples of fouling illustrate this safety concern.

Example 1. Significant Asiatic clam and American oyster fouling has been found in the containment cooling units of several pressurized water reactors (PWRs). Containment cooling units are used during both normal and accident conditions to remove heat from the containment building. From a safety standpoint, their most critical operation occurs during a loss of coolant accident (LOCA). During a LOCA, the containment cooling units function either independently or in combination with the containment spray system to condense high pressure steam escaping from the primary loop. Condensation ensures that temperature and pressure in the containment vessel do not rise above allowable design levels. Fouling of the containment cooling units caused the shutdown of one plant while the coolers were being cleaned and restored to their design flow capacity.

Example 2. At one nuclear plant that pumped its cooling water from an estuary, American oysters that has grown in the supply headers were pumped into the residual heat removal (RHR) cooling loops. American oysters did not actually grow in the RHR cooling loops, but relic shells from the supply headers nonetheless caused severe flow blockage and subsequent damage of the heat exchangers. In this incident, the plant lost its capacity to remove residual heat and was forced to provide an alternate cooling path using the spent-fuel heat exchangers.

SAFETY CLASSIFICATIONS

Systems and components within nuclear power plants are designed, fabricated, installed, and tested at a level commensurate with their importance to plant safety. Nuclear Safety Classes 1, 2, and 3 and non-nuclear Safety Class 4 ("other") correspond to safety classes A, B, C, and D, respectively, in Regulatory Guide 1.26 (U.S. AEC 1974). Brief definitions of the four safety classes are as follows:

- Safety Class 1: Applies to components of the reactor coolant pressure boundary or core support structure.
- Safety Class 2: Applies to those structures, systems, and components other than raw water or Class 1 systems that are necessary to: 1) insert negative reactivity to shut down the reactor; 2) prevent rapid insertion of positive reactivity; 3) provide emergency core cooling; 4) provide and maintain containment; 5) remove residual heat from the reactor; and 6) store spent fuel.
- Safety Class 3: Applies to structures, systems, and components that are not Safety Class 1 or 2 but which function to process radioactive

wastes (in certain instances) or which provide or support any safety system function.

- Non-nuclear Safety Class 4: Applies to structures, systems, and components in the turbine-generator or other portions of the plant that have no direct safety function but are connected to or influenced by equipment within Safety Classes 1, 2, or 3.

According to these definitions, raw-water systems may be nuclear Safety Class 3, non-nuclear Safety Class 4, or non-safety related. The systems of primary concern from a safety standpoint are those rated nuclear Safety Class 3. These raw-water systems typically serve the systems located in the reactor and auxiliary buildings. The fire protection system is also significant from a safety standpoint and is typically rated non-nuclear Safety Class 4.

FACTORS RELATED TO SAFETY CLASSIFICATION

Five factors related to the safety significance of individual Class 3 systems have been identified. The following paragraphs briefly describe the relationship of these factors to plant safety. No attempt is made here to rate the relative safety significance of these factors.

Safety Class of Systems/Components Supported by Raw-Water Systems

The safety class of other systems and components served indicates whether or not a specific Class 3 component affects systems of a higher safety class. Fouling in Class 3 components that serve class 1 or 2 systems may be of greater safety significance than fouling in those that serve other Class 3 systems.

Direct and Indirect Decay Heat Removal

Raw-water systems that directly remove decay heat may be of greater safety significance than those indirectly related to decay heat removal or those which are not related at all. Systems that remove decay heat maintain or restore appropriate water levels in the reactor coolant system, remove heat from the core during normal and accident conditions, and provide emergency core cooling. The most notable components responsible for direct removal of decay heat are the RHR heat exchangers in pressurized water and boiling water reactors (BWRs). Examples of components indirectly related to decay-heat removal are RHR pump-motor coolers, core-spray pump room coolers, and containment-spray pump room coolers.

Emergency Power-Supply Cooling

Emergency power-supply cooling refers to the raw-water cooling loops used to cool the emergency motor-generator sets (typically diesel driven) at all nuclear power plants. If these heat exchangers become inoperable as a result of fouling, the motor-generator sets are also considered inoperable.

Remedial Action Required by Component Inoperability

Inoperability of some components requires immediate shutdown for repairs, whereas other components are allowed to remain out of service for hours, days, or possibly weeks while repairs are made. Technical specifications describe the remedial actions that should be taken when components become inoperable. The specifications typically require action within a prescribed time period. The time period allowed for completion of the remedial action is an indication of the safety significance of the component.

Functional Requirements During An Emergency

The functional requirements of systems during emergency conditions also indicate safety significance. Components whose operation is initiated during emergency conditions may be of higher safety significance than those that also operate during normal conditions. Also, some safety-related components used during normal operation are isolated during emergency conditions. These systems, since they are not required during emergency conditions, may be of a lower safety priority than those which remain in operation during normal and emergency conditions.

BIVALVE FOULING RELATED TO SAFETY

Bivalve fouling affects plant operation and safety. Safety problems related to design or inoperability can be mediated by maintainance and repair, whereas safety problems related to biological fouling change with environmental factors (e.g., season, temperature, number and type of bivalves present) and plant operating conditions (e.g., flow patterns and velocities). Therefore, surveillance and control measures for bivalve fouling will be more complicated than those for mechanical problems.

METHOD FOR ASSESSING FOULING POTENTIAL OF RAW-WATER SYSTEM COMPONENTS

Score sheets can be used to assess the relative fouling potential of specific systems and components within the overall raw-water system. The score sheets presented in this chapter were developed from information contained in later chapters of this report and are designed to help NRC reviewers and power plant licensees assess what components are most likely to foul. The information can be used to implement surveillance measures to control possible fouling problems.

Although the score sheets were specifically developed to rate the fouling potential of safety-related raw-water systems, they will work equally well on non-safety systems. Sample score sheets have been provided to demonstrate their use.

Before the score sheets are introduced, characteristics of Asiatic clams, blue mussels, and American oysters as well as design characteristics of raw-water systems are summarized to help the reader understand the basics of biological fouling.

PRIMARY BIVALVE OR DESIGN CHARACTERISTICS THAT ENHANCE FOULING

Fouling occurs when the biological characteristics of bivalves are compatible with the environment in the raw-water system. Both physical design and operating procedures of raw-water systems can promote or restrict fouling. The major relationships that influence Asiatic clam, blue mussel, and American oyster fouling are described for each species. These relationships are described as "primary" characteristics because they can independently determine whether or not fouling will occur.

Bivalves Present in Raw-Water Source

If a raw-water source contains bivalves, a power plant will likely have fouling problems. Screens may prevent the entrance of adult bivalves but will probably not prevent the entrance of larvae or juveniles. After larvae or juveniles enter a system, they attach to suitable substrates and grow to maturation.

Adult Asiatic clams release larvae when the larvae are approximately 50 by 220 μm in size. Larvae remain free-floating, usually moved along by currents, until they find suitable substrates to inhabit.

Blue mussel larvae range between 90 and 305 μm in length and are free-swimming after their release from the adult. During this period, blue mussel larvae can be pumped into systems which use raw water.

American oyster larvae are 60 to 350 μm long when they are released from the adult. They remain planktonic until they find a suitable substrate on which to settle.

Minimum Flow Velocity During System Operations

The fate of bivalves within a raw-water system is partially dependent on flow rates within the system. If velocities are too fast to allow settlement, bivalves will not become established. If the currents carry the larvae or juveniles into a stagnant environment, they may not survive because food and oxygen are not replenished. Fouling should be evaluated near areas such as corners and constrictions, where flow velocities are likely to favor settlement and growth.

Flow velocities greater than 0 but less than 0.3 meters per second (0.3 mps = 1 foot per second, fps) allow Asiatic clam larvae to settle. Flow velocities that allow Asiatic clam larvae to settle are found in the corners of intake structures, inlets to heat exchanger water-boxes, and components where the flow path widens suddenly.

Flow velocities greater than 0.1 mps but less than 1.2 mps (0.3 to 4 fps) allow blue mussel larvae to settle. Flow velocities below 0.1 mps may not provide adequate food and oxygen or remove metabolic wastes fast enough to allow dense blue mussel growth. Continuous- and intermittent-flow systems are most often affected by blue mussel fouling. Near-stagnant conditions do not provide adequate food and oxygen for blue mussels. Blue mussels are able to attach firmly to their substrate by secreting a byssal thread and can tolerate flow velocities up to approximately 3.4 mps (11.4 fps). Flow velocities in this range exist in practically all raw-water cooling loops in plants where blue mussel fouling has occurred.

Flow velocities greater than 0 but less than 1.2 mps (4 fps) allow American oyster larvae to settle. American oysters are able to attach firmly to piping and intake structures by cementing themselves to their substrate. They can tolerate velocities above 1.2 mps after attachment. Flow velocities in this range exist in practically all cooling loops of raw-water systems.

Water Temperature

Water temperatures greatly influence the presence and growth of bivalve populations. Temperatures greater than or less than tolerable limits will preclude bivalves. Assessments of bivalve presence in or near power plants must take into consideration both the temperature of the water source and the water temperatures attained during different operating conditions of the power plant. Water temperatures within a raw-water system range from ambient (source water) temperatures to greater than 30°C.

Water temperatures between 2° and 35°C support Asiatic clam growth. Optimum temperatures for growth are in the mid 20°C range. Optimum temperatures for reproduction are from 15° to 28°C. Favorable temperatures 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° and 26°C support blue mussel growth. Optimum temperatures for growth range between 10° to 20°C. The optimum temperature for reproduction is about 15°C. Optimum temperatures depend on the mussels' normal seasonal temperature range, which varies with latitude. Favorable temperatures for blue mussel growth are found in intake structures and in intake piping and tubing upstream of the main condensers.

Water temperatures between 1° and 36°C support American oyster growth. Optimum temperatures for growth range is about 25°C. The optimum temperature for reproduction is about 15°C. Favorable temperatures for American oyster growth are found within the intake piping from the intake to the main condensers, within the intake bays, and on the inlet side of the main condensers.

Chlorination

Bivalve growth and survival can be retarded by the introduction of chemicals into the environment. All power plants use an antifoulant system or have contingencies for antifoulant systems. Intermittent chlorination to control slime is ineffective in controlling larvae and adult bivalves. Bivalves can avoid antifoulant chemicals by burrowing into substrates.

A characteristic of mollusk bivalves is their ability to close their shells in response to environmental stimuli. Bivalves avoid inimical environmental conditions by retreating into their shells and respiring anaerobically for extended periods of time. This behavior allows adult Asiatic clams, blue mussels, and American oysters to avoid antifoulant control measures such as chlorination. Effective antifoulant systems must therefore be designed to overcome the natural protective abilities of bivalves.

Chlorination may be ineffective in controlling Asiatic clams when:

- the system is chlorinated intermittently
- residual chlorine levels do not exceed 0.6 ppm
- chlorinators are inoperative for extended periods.

Blue mussels are able to avoid inimical water conditions by closing their shells. Therefore, low-level continuous chlorination of 0.25 ppm or greater is required year around to control blue mussel fouling (Roberts 1976).

A chlorination system that is unreliable will defeat the effectiveness of continuous chlorination. In addition, components of the service-water system that may receive less than continuous chlorination are:

- all components upstream of the chlorine injection system
- components not in use during chlorination
- components far downstream of the injection point
- components with silt accumulations having a high demand for chlorine..

Continuous chlorination at free residual chlorine levels of 0.20 ppm or above are required year around to effectively control the settlement of American oyster larvae. Unreliable chlorination systems severely impair the effectiveness of continuous chlorination.

Chlorination may not effectively control American oyster fouling when:

- the system is chlorinated intermittently
- residual chlorine levels do not exceed 0.6 ppm
- chlorinators are inoperative for extended periods.

SECONDARY FOULING CHARACTERISTICS

Numerous characteristics of bivalves and raw-water systems influence fouling but are secondary to the primary characteristics described previously. For example, the presence of suitable substrate is important only if bivalves are present. Secondary characteristics that influence Asiatic clam, blue mussel, and American oyster fouling are described below for each species.

Flow Frequency

Intermittently used systems are typically fouled by Asiatic clams. These systems often provide ideal conditions for the settlement of silt and Asiatic clam larvae. Approximately 80% of the raw-water cooling loops in plants where Asiatic clam fouling has occurred exhibit intermittent or near-stagnant flow conditions.

Blue mussel and American oyster fouling occurs in both intermittent and continuous-flow systems. American oysters can tolerate near-stagnant flow conditions.

Diameter of Supply Piping and Heat Exchanger Tubing

Water flow in many small components of raw-water systems can be blocked or diverted by the accumulation of Asiatic clam shells. Early detection of Asiatic clam fouling should focus on low velocity areas in the intake (corners primarily), on areas where silt is known to accumulate, and on small components [e.g., 50mm (2-in.) and smaller piping, small heat exchangers, room coolers], where Asiatic clams and relic shells first accumulate.

- Asiatic clams and relic shells are most often found in piping of 100 mm (4 in.) or smaller diameter.
- Chronic flow blockages from Asiatic clams, silt, and corrosion products have occurred in 50 mm (2 in.) and smaller piping.
- Heat exchangers with tube diameters of 13 mm (1/2 in.) or smaller have clogged most readily (room coolers are typical).

Blue mussel fouling appears to occur most readily in large components such as intake structures and raw-water supply headers. Fouling of large components generally precedes the interruption of flow to heat exchangers. The following areas are particularly susceptible to clogging by blue mussels:

- heat exchanger tubes and tube sheets
- small components (e.g., heat exchanger tubes, small piping) and constrictions.

American oyster fouling at one plant surveyed was most dense in the intake structure and in the large raw-water headers. Densities decreased at higher elevations and at piping farther into the plant. American oysters gravitated to lower areas and were less dense farther into the plant because of reduced oxygen and food in the raw water. Operating transients (thermal shock, water hammer, earthquake, etc.) may cause shells to break off and clog small components. Shell accumulations in small components, however, may not occur until after substantial American oyster fouling has occurred in large components.

Silting and Corrosion Potential

Some areas within raw-water systems accumulate silt and mud, which are suitable substrates for bivalve settlement. Many other substrates are also available to bivalves in a raw-water system. The extent of bivalve fouling is partially determined by the availability of suitable substrates within the service-water system.

Densities of Asiatic clams will vary with the substrates in the waterbody (Eng 1979). Asiatic clams seem to prefer sandy or gravel substrates but are also found in larger rock or in mud or silt (Britton 1982). In service-water systems, Asiatic clams appear to be associated with accumulations of silt or corrosion products. It is not clear, at this time, if this association is causitive or incidental.

Silt and corrosion products occur in:

- low-velocity flow areas
- fire-protection systems and piping of 50 mm (2 in.) or smaller diameter
- low elevations or piping where elevations change suddenly.

Young blue mussels will settle on all types of firm substrata that have either a rough or discontinuous surface (Maas Geesteranus 1942). Larvae can attach and detach themselves many times before establishing themselves permanently. Some substrates, such as silt, may inhibit blue mussel settlement and growth. Silt reduces the filtering efficiency of blue mussels and thus reduces their uptake of food and oxygen.

Areas that provide suitable substrates for blue mussel settlement include:

- floors and walls of intake structures
- raw-water supply headers.

American oyster larvae generally attach to shells but will also attach to rocks and other surfaces. The following order of substrate preference has been noted (Butler 1954): cement board; American oyster shell; frosted glass; black plexiglass; white plexiglass.

Silt may not have a pronounced positive or negative effect on American oyster settlement. American oysters are more tolerant of suspended silt than are blue mussels. High levels of silt have been found with American oysters in a plant located on a river near Chesapeake Bay.

American oyster settling is heaviest in the following components of raw-water systems:

- the intake bay
- intake piping to the main condensers, the reactor building and turbine building closed cooling-water sytems, and the RHR heat exchangers.

Valve Leak Potential

Valve leaks are a primary cause of low-velocity flow. Butterfly valves have the highest leak potential. These valves are commonly used to regulate flow through intermittent-flow cooling loops. Leaks also tend to develop in gate valves.

Valve leaking varies with the type of valve:

- Butterfly valves have the highest leak potential.
- Gate valves have the second highest leak potential.
- Globe and ball valves are least likely to leak.

Valves also constrict flow and trap shells, which further exacerbates the fouling problem.

Fouling History In-Plant or at Nearby Industrial Plants

Fouling can be predicted, in part, by assessing past occurrences of fouling in other power plants or in nearby industrial plants. At new plants, fouling potential can be assessed by examining fouling problems at other plants that use similar sources of water. Knowing what systems or components are most likely or least likely to be fouled also helps determine the fouling potential of a plant.

Common locations where Asiatic clams have been found in nuclear power plant service-water systems include:

- low-velocity flow areas in intake structures.
- branch headers supplying water to intermittent-flow cooling loops.
- auxiliary-building room coolers to: low-pressure safety-injection pumps, high-pressure safety-injection pumps, electric equipment rooms, and RHR pump rooms.
- other components such as containment cooling units; containment spray-pump seal coolers; diesel generator coolers; service-water strainers; fire protection systems; control-room and computer-room air coolers; administration building HVAC coolers, generator, hydrogen coolers; main condensers and circulating-water piping; component cooling-water heat exchangers; and RBCCW and TBCCW heat exchangers.
- all raw-water cooling loops.

Uncommon locations for significant Asiatic clam fouling in nuclear power plant service-water systems include:

- large, continuous-flow cooling loops with an average flow velocity greater than 1 mps (3.3 fps), e.g., component cooling-water heat exchangers, RBCCW and TBCCW heat exchangers, main condensers, and circulating-water piping.

Common locations where blue mussel fouling has occurred include:

- floors and walls of intake structures (accumulations up to 1.2 m thick)
- raw-water supply headers to RBCCW and TBCCW heat exchangers; diesel-generator coolers; main condensers, and circulating-water piping
- RBCCW and TBCCW heat exchangers; diesel-generator coolers; and main condensers
- all raw-water cooling loops.

All locations within the raw-water system of a nuclear power plant are amenable to blue mussel fouling.

Locations where American oyster fouling has occurred include:

- floors and walls of intake structures
- raw-water headers immediately downstream from the intake
- all raw-water cooling loops
- other components such as the RHR heat exchangers; diesel-generator water-jacket coolers; V-ball throttle valves to containment-fan cooling units; safety injection-pump lube-oil coolers; containment spray-pump room coolers; charging-pump room coolers; RHR-pump room coolers; and main condensers and circulating-water pipe.

Uncommon locations for American oyster fouling include:

- raw-water piping at high elevations and far downstream from the intake
- high-velocity (2.4 mps or 8 fps), continuous flow components of the circulating-water system.

SCORE SHEETS TO RATE FOULING POTENTIAL OF RAW-WATER SYSTEMS

Score sheets to evaluate fouling by Asiatic clams, blue mussels, and American oysters are shown in Figures 4, 5, and 6, respectively. The scoring system gives high scores to raw-water systems and components which exhibit conditions that are known to cause fouling, and low scores to systems and components that exhibit conditions which are known to inhibit fouling.

The score sheets list design and operating characteristics of raw-water systems that either enhance or inhibit fouling. The sheets are separated into primary and secondary characteristics. Primary fouling characteristics such as bivalve occurrence, flow velocity, water temperature, and the effectiveness of chlorination practices can independently determine whether or not fouling will occur. Secondary characteristics such as flow frequency; pipe and tubing size; and silting, corrosion, and valve-leak potential do not have as pronounced an effect on fouling as do the primary characteristics.

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

Numerical Values for Rating Fouling Potential

Primary characteristics are assigned numerical values ranging from -5 to 5. Because each primary characteristic relates to a basic requirement for bivalve survival or growth, one or more -5 scores indicates 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 or secondary characteristics.

System/Component: ______________________________

PRIMARY FOULING CHARACTERISTICS	Circle Your Evaluation	Circle Maximum When Applicable
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		
0 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 OF 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, eddie 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, and
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 4. Score Sheet to Assess Asiatic Clam (*Corbicula fluminea*) Fouling in a Nuclear Power 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

	Circle Your Evaluation	Circle Maximum When Applicable
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 Relic Shells		
Piping 4 inches in diameter and smaller	3	
Low spots in cooling loops	4	
Heat exchanger tubes, tube sheets, 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, and
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 5. Score Sheet to Assess Blue Mussel (*Corbicula fluminea*) Fouling 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	
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 leats 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 OF 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 Relic Shells**		
Piping 4 inches in diameter and smaller	3	
Low spots in cooling loops	4	
Heat exchanger tubes, tube sheets, 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, and
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 6. Score Sheet to Assess American Oyster Fouling in a Nuclear Power Plant Service-Water System

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

It is recommended that actual operating conditions be used when assigning numerical values to the fouling characteristics. This is especially important for estimating the contribution of flow velocity to the overall fouling potential. Utility personnel indicate that actual flow rates may vary substantially from design flow rates. During operating conditions such as cold shutdown or low-power testing, flow velocities may be one-half the average velocity of the design flow rate. Thus, design flow velocities may be high enough to prevent bivalves from fouling, whereas the actual flow velocities may be ideal for fouling. If excessive valve leaks are known 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.

In some cases, scores for primary and secondary characteristics may be 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 acute. For example, assume that a certain component has a low primary potential for American oyster fouling and a high secondary potential, and that the primary potential is low only because the flow velocity is high enough that American oysters cannot settle. If the plant were to operate at a reduced flow, the potential for fouling would increase substantially. Reduced flow velocity has, in fact, caused accelerated American oyster fouling at two power plants.

Calculation of Fouling Index

A fouling index is calculated as the ratio of the sums of actual scores to maximum scores. The index can range from 1.0 to less than zero. The closer the index value is to 1.0, the greater the fouling potential of the system or component. Values less than zero can occur when there is more than one -5 evaluation score. Fouling characteristics that are not scored are simply left out of the scoring process. Some characteristics pertain only to plants with previous operating experience (see asterisks on Figures 4, 5, and 6) and should be omitted when estimating the fouling potential of plants that are currently in the design or construction phase. Even the lowest score does not guarantee that fouling will not occur, only that the potential for fouling by bivalves is low.

Examples of Score Sheet Use

The following examples show how the score sheets can be used to estimate the fouling potential of several components in raw-water systems. The examples include components which have fouled readily and others that typically exhibit little fouling.

Asiatic Clams

Asiatic clams tend to foul small, intermittently used heat exchangers such as RHR-pump room coolers. Conversely, large, continuous-flow heat exchangers such as component-cooling water heat exchangers do not foul as readily. The important characteristics of these two heat exchangers that apply to Asiatic clam fouling are described below.

For these examples, it is assumed that the source water temperature varies between 5° and 28°C throughout the year, the service-water system is chlorinated once a week for 30 minutes at a level of 0.5 ppm free residual chlorine, and Asiatic clam larvae have been found in the water source of the plant during the past year.

Minimum operational flow velocity through inlet piping to the RHR-pump room cooler is about 0.5 mps (1.6 fps). Heat-exchanger tube diameters are 13 mm (0.5 in.) or smaller. Inlet piping is made of 38-mm (1.5-in.)-diameter carbon steel. Flow through the heat exchanger is intermittent. A butterfly valve is used to throttle flow. Silt and occasionally relic shells have been found in the heat exchanger during previous inspections. The score sheet for the RHR-pump room cooler is shown in Figure 7.

Flow velocity through the inlet piping to the component cooling-water heat exchanger during full-power operation is 2.3 mps (7.7 fps) and during cold shutdown is 1.2 mps (3.8 fps). Tube diameters range from 16 to 22 mm (5/8 to 7/8 in.). Inlet piping is 760-mm (30-in.)-diameter stainless steel. Flow through the system is continuous. A butterfly valve is used to throttle flow. Few relic shells have been found in the heat exchanger during past inspections. No silt was found during inspections. The score sheet for the component cooling-water heat exchanger is shown in Figure 8.

The RHR-pump room cooler has a higher overall fouling index (0.85, Figure 7) than the component cooling-water heat exchanger (0.40, Figure 8). Scores of 0.50 or less on the primary characteristics alone may be sufficient to indicate low fouling potential, because primary scores of 0.50 or lower can only occur if one or more of the basic environmental requirements for bivalve fouling is missing.

Blue Mussel

Blue mussel fouling occurs initially and is most prevalent in large cooling loops such as the RBCCW cooling loops. Flow velocity in these loops, which are used continuously, often drops below 1.2 mps (4 fps). The backup RBCCW

System/Component: RHR-pump room cooler

PRIMARY FOULING CHARACTERISTICS

	Circle Your Evaluation	Circle Maximum When Applicable
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		
0 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 (>0.6 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	16	
SUM OF CIRCLED MAXIMUMS		20

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, eddie 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	28	
SUM OF CIRCLED MAXIMUMS		32

$$FI = \frac{PS + SS}{PM + SM} = 0.85$$

where:
FI = FOULING INDEX
PS = Primary Sum,
SS = Secondary Sum,
PM = Primary Maximum, and
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 7. Assessment of Asiatic Clam Fouling in a Nuclear Power Plant Service-Water System Residual Heat Removal Pump Room Cooler

System/Component: Component Cooling-Water Heat Exchanger

PRIMARY FOULING CHARACTERISTICS

	Circle Your Evaluation	Circle Maximum When Applicable
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		
0 or greater than 2 fps	[✓ -5]	
1 to 2 fps	3	
less than 1 fps	5	[✓ 5]
Normal 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 >0.6 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	8	
SUM OF CIRCLED MAXIMUMS		20

SECONDARY FOULING CHARACTERISTICS

	Circle Your Evaluation	Circle Maximum When Applicable
Flow Frequency		
Continuous Flow	[✓ 1]	
Intermittent Flow	5	[✓ 5]
Supply Piping Size		
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, eddie 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	13	
SUM OF CIRCLED MAXIMUMS		32

$$FI = \frac{PS + SS}{PM + SM} = 0.40$$

where:
FI = FOULING INDEX
PS = Primary Sum,
SS = Secondary Sum,
PM = Primary Maximum, and
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 8. Assessment of Asiatic Clam Fouling in a Nuclear Power Plant Service-Water System Component Cooling-Water Heat Exchanger

cooling loop tends not to foul as much as the loop in normal service, because near-stagnant flow conditions inhibit the dense growth of blue mussels. Leaking valves, however, may allow blue mussel fouling in the backup systems to be greater than expected. Sample score sheets for in-service and backup RBCCW loops are shown in Figures 9 and 10. The important characteristics of the RBCCW cooling loops are listed below. The temperature of the water source ranges from 0° to 20°C throughout the year. The plant chlorinates for 1 hour per day at 0.25 ppm free residual chlorine to control slime.

Minimum normal flow in the RBCCW cooling loops is 0.6 mps (2 fps). The RBCCW header is made of 310-mm (12-in.)-diameter carbon steel and is lined with rubber. One RBCCW cooling loop is used continuously; the other is in standby and has nearly stagnant flow conditions. Butterfly valves are used to regulate flow. Live blue mussels have been found attached to the RBCCW headers. Blue mussel density in the backup loop is less than in the in-service header. Relic shells have been found in the RBCCW heat exchangers, and a few shells have been found in the backup loop.

The score sheets in Figures 9 and 10 show fouling indices of 0.94 and 0.83, respectively, for the in-service and standby cooling loops. This indicates a high potential for fouling in each cooling loop, but gives a slightly higher fouling potential to the in-service loop.

American Oyster

American oyster fouling often occurs first in large components such as the intake structure and the main raw-water headers. During normal, full-power operation, the flow velocity in the headers often exceeds the flows that allow American oysters to settle. During plant operating phases such as cold shutdown or low-power testing, however, the flow velocities may be low enough to allow American oysters to settle and attach. After American oysters have attached to the inside surface of the header, the increased flow velocities during full power operation are not likely to remove them. The RHR heat exchangers are located at a lower elevation than the supply or discharge piping and, therefore, act as natural traps for American oyster shells that have broken off farther upstream in the supply headers. American oyster growth is not a problem in the RHR supply piping itself, because the RHR cooling loops are normally in standby and are purged with well water.

Sample score sheets for the raw-water supply headers and the RHR heat exchangers are shown in Figures 11 and 12. The temperature of the water source is assumed to vary from 10°C in mid-winter to 25°C in late summer. American oyster populations are known to occur in the vicinity of the plant. Recent drought conditions have increased the salinity of the river used as the plant's raw-water source, allowing American oysters to migrate up the river. The plant currently chlorinates three times a day for periods of 30 minutes at 1 ppm free residual chlorine to control slime.

System/Component: In-Service RBCCW Header

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 plan.	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	20	
SUM OF CIRCLED MAXIMUMS		20

SECONDARY FOULING CHARACTERISTICS

	Circle Your Evaluation	Circle Maximum When Applicable
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 Relic Shells**		
Piping 4 inches in diameter and smaller	3	
Low spots in cooling loops	4	N/A
Heat exchanger tubes, tube sheets, 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	13	
SUM OF CIRCLED MAXIMUMS		15

$$FI = \frac{PS + SS}{PM + SM} = 0.94$$

where:
FI = FOULING INDEX
PS = Primary Sum,
SS = Secondary Sum,
PM = Primary Maximum, and
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 9. Assessment of Blue Mussel Fouling in a Nuclear Power Plant Service-Water System In-Service RBCCW Header

System/Component: Standby RBCCW Header

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	20	
SUM OF CIRCLED MAXIMUMS		20

SECONDARY FOULING CHARACTERISTICS

	Circle Your Evaluation	Circle Maximum When Applicable
Flow Frequency		
Normally stagnant (near stagnant)	[✓ 1]	
Intermittent	3	
Continuous	5	[✓ 5]
Valve Leak Potential		
Ball or globe valve	1	
Gate valve	3	
Butterfly valve	[✓ 5]	[✓ 5]
***Natural Traps for Relic Shells**		
Piping 4 inches in diameter and smaller	3	
Low spots in cooling loops	4	N/A
Heat exchanger tubes, tube sheets, 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	9	
SUM OF CIRCLED MAXIMUMS		15

$$FI = \frac{PS + SS}{PM + SM} = 0.83$$

where:
FI = FOULING INDEX
PS = Primary Sum,
SS = Secondary Sum,
PM = Primary Maximum, and
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 10. Assessment of Blue Mussel Fouling in a Nuclear Power Plant Service-Water System RBCCW Header on Standby

System/Component: Raw-Water Header

PRIMARY FOULING CHARACTERISTICS

	Circle Your Evaluation		Circle Maximum When Applicable
American Oysters 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 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	18		
SUM OF CIRCLED MAXIMUMS			20

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	N/A	
Butterfly valve	5		5
* **Natural Traps for Relic Shells**			
Piping 4 inches in diameter and smaller	3		
Low spots in cooling loops	4	N/A	
Heat exchanger tubes, tube sheets, 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	8		
SUM OF CIRCLED MAXIMUMS			10

$FI = \frac{PS + SS}{PH + SH} = 0.87$

where:
FI = FOULING INDEX
PS = Primary Sum,
SS = Secondary Sum,
PM = Primary Maximum, and
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 11. Assessment of American Oyster Fouling in a Nuclear Power Plant Service-Water System Raw-Water Header

System/Component: RHR Heat Exchanger

PRIMARY FOULING CHARACTERISTICS	Circle Your Evaluation	Circle Maximum When Applicable
American Oysters 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 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	10	
SUM OF CIRCLED MAXIMUMS		20
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	N/A
Butterfly valve	5	5
*** Natural Traps for Relic Shells**		
Piping 4 inches diameter and smaller	3	
Low spots in cooling loops	[✓ 4]	
Heat exchanger tubes, tube sheets, 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	10	
SUM OF CIRCLED MAXIMUMS		15

$$FI = \frac{PS + SS}{PM + SM} = 0.57$$

where:
FI = FOULING INDEX
PS = Primary Sum,
SS = Secondary Sum,
PM = Primary Maximum, and
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 12. Assessment of American Oyster Fouling in a Nuclear Power Plant Service-Water System RHR Heat Exchanger

Minimal normal flow in the raw-water supply header is about 2.1 mps (7 fps) during normal operation and 1.1 mps (3.5 fps) during cold shutdown. The headers are 30 in. in diameter and are made of carbon steel. Flow through the headers is continuous. American oysters have been found in the raw-water source for the plant. The last inspection of the raw-water header (1 year ago) did not show any American oysters in the raw-water headers.

Minimum normal flow through inlet piping to the RHR heat exchangers is about 3.0 mps (10 fps) during normal shutdown and 1.8 mps (6 fps) during cold shutdown. Inlet piping is 310 mm (12 in.) in diameter and is made of stainless steel. The RHR heat exchangers are located approximately 3 m (10 ft) below the elevation of the supply and discharge headers. RHR heat exchangers are used during normal shutdown, sustained cold shutdown, or accident conditions. They are normally in standby condition and are purged with demineralized water.

Figures 11 and 12 show the completed score sheets for the raw-water headers and the RHR heat exchangers. The indices for the raw-water headers and the RHR heat exchangers are 0.87 and 0.57, respectively. This indicates a high fouling potential for the raw-water headers and a low-to-medium potential for the RHR heat exchangers. However, at the plant where these examples were patterned after, the most serious problem has occurred in the RHR heat exchangers. The actual density of American oysters (fouling) was greater in the supply-headers, but fouling in the supply-header had clogged the RHR heat exchangers. The score sheet correctly indicates a higher fouling potential to the raw-water header, because fouling will most likely occur in the headers before clogging occurs in the RHR heat exchangers.

Limitations of Fouling Index

The fouling indices calculated with these score sheets might not accurately predict fouling potential for all systems and components under all operating conditions. The score sheets are designed to evaluate general system-related characteristics that influence fouling potential. This "general" approach reduces the sensitivity of the score sheets somewhat by not considering a number of more specific characteristics that also affect fouling. The general approach is necessitated partly by the lack of detailed operating data concerning histories of events leading up to fouling incidents. Many characteristics such as dissolved oxygen content, pH, and salinity do affect fouling but may be difficult to determine in an operating nuclear power plant.

Two Examples of Fouling Index Limitations

The score sheets may also fail to address uncommon conditions that occur at certain plants. These conditions may, in some instances, either cause or prevent fouling. For example, Asiatic clam fouling has occurred in the circulating-water system of one plant where the intake structure remained full of raw-water during the final construction of the plant. Initial startup of the circulating-water pumps caused extensive flow blockage of the main condensers. If the design flow velocity and normal operating conditions were used to estimate the fouling potential of the condensers (flow velocity of 2.4 mps (8 fps) or greater, large system, continuous flow), the score sheet would give a very low fouling index. In this case, the atypical, near-stagnant conditions in the circulating-water system allowed fouling to occur.

The score sheets may also indicate fouling will be a problem when, in fact, it will not. One plant, for example, normally shuts down during the late-spring and summer months because of the decreased demand for power and the increased supply of hydro-electric power in the region. Asiatic clams are found in the water source and in the plant, but fouling is not a problem. Plant personnel attribute the lack of fouling, in part, to the fact that a number of the raw-water systems are drained during the yearly outage. The dewatered environment that exists in these systems for 4 to 5 months each year does not allow Asiatic clams to survive year around. Regardless of the fouling potential estimated by the score sheets, serious fouling is not likely to occur in these systems.

In certain instances, one or two of the fouling characteristics may dominate the evaluation and mask other effects of clogging. This phenomena was shown in a previous example (Figure 12) of American oyster fouling in the RHR heat exchangers. The score sheet predicted a relatively low fouling potential, when in fact serious American oyster shell clogging has damaged the heat exchangers. The score sheet correctly predicted that American oysters were not likely to grow in the RHR cooling loops, but failed to recognize the importance of the RHR heat exchangers acting as natural traps for shells.

Summary of Fouling Index Advantages and Limitations

Use of a fouling index to assess fouling or clogging has the following benefits:

- The fouling index can predict the relative fouling potential of numerous systems or components in the overall raw-water system.
- A surveillance program based on relative fouling potential can 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 thus apply to plants over a wide geographic region.
- Utilities that have fouling problems can use the fouling index as a guideline for developing a more detailed system to evaluate their fouling problems.

Use of a fouling index to assess fouling or clogging has the following limitations:

- The fouling index may not accurately predict fouling potential for all systems or components under all operating conditions.
- The index may not address uncommon operating conditions that occur at certain plants.
- The index lacks some sensitivity because of the generality of the characteristics used.
- The index may not accurately reflect the characteristic that is controlling fouling or clogging within a specific system.

CORRELATIONS BETWEEN RAW-WATER SYSTEM DESIGN AND BIVALVE CHARACTERISTICS THAT ENHANCE FOULING

Design characteristics of raw-water systems may allow or even enhance bivalve fouling by promoting conditions conducive to bivalve growth. PNL's review indicates that the following characteristics of raw-water systems influence fouling: 1) component size, 2) flow velocity and flow patterns, 3) suitable areas for settlement and growth, 4) water temperatures that enhance bivalve growth, and 5) an environment that allows bivalves to avoid natural or artifical population controls. These characteristics, when correlated with the biological characteristics of bivalves, served as the outline for the fouling score sheets described in the previous chapter.

Fouling in fire protection systems is addressed at the end of this chapter.

COMPONENT SIZE

Bivalve larvae and juveniles are small enough to pass through service-water screens and strainers. As the bivalves grow to adult size, their shells can clog small piping or create other constrictions within a system.

Asiatic clam fouling most often manifests itself in small-diameter components of the service-water, auxiliary-cooling water, and fire protection systems. One utility indicated that fouling from Asiatic clams, silt, and corrosion products is most prevalent in pipes that have diameters of 100 mm (4 in.) and smaller, and that chronic fouling occurs in pipes that have diameters of 50 mm (2 in.) and smaller. For example, fouling occurred in 76 mm (3 in.) supply lines to the containment cooling units. The utility has replaced most of its small-diameter carbon steel piping with stainless steel piping to prevent corrosion. It has also replaced service-water system piping of less than 25 mm (1 in.) in diameter with 25-mm (1-in.)-diameter stainless-steel piping.

Several utilities have indicated that heat exchangers with tube diameters of 13 mm (1/2 in.) or smaller foul more readily than ones with larger diameters. Some have also noted that room coolers frequently foul with buildups of silt, corrosion, and Asiatic clams. Room coolers typically have supply piping less than 100 mm (4 in.) in diameter and tube diameters that are 13 mm (1/2 in.) and smaller. Asiatic clam fouling is not, however, restricted to heat exchangers with tube diameters of 13 mm (1/2 in.) or smaller. Several utilities have reported clogging of the main condensers, which typically have tube diameters of 22 to 25 mm (7/8 to 1 in.). A notable example of this occurred at one plant after the circulating-water intake bays were allowed to remain filled with raw-water while construction of the plant was completed. When the circulating-water pumps were started, Asiatic clams and silt were sucked into the condensers. Many of the Asiatic clam shells became wedged inside the condenser tubes, and others where trapped against the tube sheet. Adult Asiatic clams typically range in size up to 32 mm (Goss and Cain 1977), and many are of ideal size to enter heat exchanger tubes and become wedged there.

Utility personnel have also noticed that condenser tubes 22 mm (7/8 in.) in diameter foul more readily than do condenser tubes 25 mm (1 in.) in diameter. The smaller tubes allow fewer live Asiatic clams and relic shells to pass through.

It is not known for certain whether Asiatic clams actually settle and grow in small-diameter components or whether these are simply the locations where they accumulate after being carried into the system. Clogging in small-diameter components may be more frequent and more noticeable than in large-diameter tubes because Asiatic clam shells are more nearly the size of these components and thus block off a proportionately greater percentage of the flow. One utility, noting that approximately 90% of the fouling in heat exchangers was caused by relic Asiatic clam shells, speculated that the Asiatic clams had grown elsewhere in the system and, after dying, had been flushed into the heat exchangers. As the number of Asiatic clams in low-velocity areas increased, some of the Asiatic clams may have been forced into high-flow areas and carried through the system until they lodged in a constricted area (J. S. Mattice, unpub. manuscript, EPRI). Asiatic clams and relic shells are typically found on heat exchanger tube sheets and upstream of inlet valves to intermittent-use systems in standby mode. Both restrict flow and create areas where Asiatic clams and shells may deposit.

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. Relic shells from these bivalves have, however, been found in small-diameter piping and have clogged heat-exchanger tubes and tube sheets. These locations are similar to those where live Asiatic clams and relic shells have been found.

Two utilities have noted increased tube wear caused by blue mussel shells wedged in the condenser tubes. High velocity, turbulent flow conditions around the wedged shells cause possible cavitation and increased erosion of the tube walls. One plant stated that it had to reduce power four times during the summer of 1983 to repair tube leaks caused by blue mussels wedged in condenser tubes.

FLOW VELOCITY AND FLOW PATTERNS

Velocity and pattern are major flow-related factors that affect bivalve occurrence in raw-water systems. The magnitude and characteristics of both may vary within a raw-water system. How they very is important to the probable occurrence of bivalves. Flow velocities are affected by intermittent use of the system and by valve design and malfunction. Flow patterns are affected by plant operating transients and by component configurations such as changes in elevation, widening or narrowing of the flow path, and corners.

Intermittent Use Affects Flow Velocity

Intermittent use of systems is a primary cause of low velocity or nearly stagnant flow conditions. Systems that are used intermittently include backup cooling loops and cooling loops that are used only on demand. Backup cooling loops are used only during flow testing or when the loop that is normally in service is isolated for maintenance. During normal operation, up to 80% of the heat exchangers in freshwater open-cycle cooling systems may exhibit low velocity or nearly stagnant flow conditions. Several utilities indicate that Asiatic clam fouling typically occurs in systems with low flow, intermittent flow, or nearly stagnant conditions for extended periods of time. One utility has also reported that American oyster fouling occurred in intermittently used systems.

Intermittently used systems are typically maintained full of raw water and in standby condition. Technical specifications at power plants call for periodic flow testing to ensure the operability of these systems. Several utilities have increased the frequency of their flow tests after finding Asiatic clams in intermittently used systems. Although more frequent flow testing may flush the system of silt and small Asiatic clams, increased flow testing also provides a fresh supply of food and water to the Asiatic clams, thus providing a more habitable environment for Asiatic clams trapped in protected areas of the system.

Unlike Asiatic clams and American oysters, blue mussels do not favor systems that are used intermittently. Blue mussel fouling is heaviest in systems which provide moderate velocity, continuous-flow conditions. Stagnant or nearly stagnant conditions found in cooling loops that are used intermittently do not provide adequate food and oxygen for dense blue mussel fouling.

Both blue mussels and American oysters are able to attach to surfaces and survive in flow conditions where Asiatic clams are not often found. This is primarily because adult Asiatic clams are not able to attach to surfaces. In coastal plants where blue mussel or American oyster fouling has been a problem, fouling has most frequently occurred in systems that are used continuously and have moderate flow velocities (between 0.2 and 3.4 mps or 0.7 and 11.2 fps). Asiatic clam fouling, however, has been most prevalent in systems that are used intermittently and have low flow velocities (less than 0.3 mps or 1 fps). Examples of system components that have been most affected by blue mussels and American oysters are raw-water system headers, RBCCW and TBCCW heat exchangers, and the main condensers. Comparable, continuous-flow heat exchangers and piping in freshwater plants have not been as prone to fouling by Asiatic clams, because the flow velocities are high enough to prevent Asiatic clams from settling.

These observations lead to the conclusion that use of closed-cycle raw-water systems in future freshwater plants could reduce Asiatic clam fouling. Large, continuous-flow heat exchangers common to closed-cycle systems would not allow Asiatic clams to settle as readily as do the many small, intermittent-flow heat exchangers common to open-cycle systems currently used in freshwater plants. Larvae and small adult Asiatic clams would remain in suspension and be carried through and discharged from the plant.

Valve Design and Malfunction Affect Flow Velocity

Valve leaks are a common cause of low velocity, continuous-flow conditions in redundant and intermittently used cooling loops. Although these leaks may be minor from an engineering standpoint, the flow volume may be high enough to provide bivalves with a continuous supply of food and oxygen. These conditions are not necessarily ideal for bivalve growth but may allow bivalve populations to grow in the system. In completely stagnant systems, on the other hand, dissolved oxygen and nutrient levels may be reduced to levels that will not support bivalve growth. Oxygen and nutrient levels are reduced by bivalve respiration, filter-feeding, biological oxygen demand, and the formation of corrosion products.

Malfunctions and leaks within the design specifications of a valve are two basic types of valve leaks. Valve malfunctions may be corrected with increased maintenance, but design-allowable leaks are governed by manufacturing tolerances. Valves are designed to control flow rate and/or pressure to within specified limits. Valves used in raw-water cooling loops generally are not required to provide zero flow conditions when closed. Raw-water cooling systems are typically designed with excess pumping capacity, and thus minor valve leaks can exist while meeting the design flow requirements. Valves in the service-water system, when closed, may normally allow leaks of up to several percent of the system design flow. Several utility personnel have indicated that strictly stagnant conditions rarely exist in raw-water systems during normal operations.

Different types of valves are designed for different applications, and each have different leak characteristics. Four types of valves that are commonly used in raw-water systems are butterfly, gate, globe, and ball valves. Of these four types of valves, butterfly valves have the highest occurrence of leakage. Butterfly valves are primarily used for throttling flow in low-pressure applications where leakage is relatively unimportant. Butterfly valves are often used in raw-water cooling loops to regulate flow through heat exchangers. Gate valves are commonly used as shut-off valves in raw-water systems. They are generally designed to be used in either the fully open or fully closed position. Gate valves may be subject to accelerated wear of the valve seat and valve disk (causing leakage) when used in the partially open position to throttle flow. Gate valves are the second most common valve type to develop leaks. Globe valves and ball valves are used either as throttle or shut-off valves, and are less likely to leak than butterfly or gate valves.

One notable incident of Asiatic clam fouling has been attributed to a valve leak in the containment cooling-units of a PWR plant. Utility personnel estimated that a leaking butterfly valve allowed flow of approximately 750 to 1150 ℓpm (200 to 300 gpm) through the 300 mm (12 in.) inside-diameter supply header. Full capacity design flow for the header is 4500 ℓpm (1200 gpm). Average velocity through the header, with the valve closed, was approximately 0.17 to 0.26 mps (0.64 to 0.98 fps). These velocities are below the estimated upper limit of 0.30 mps (1.0 fps) for Asiatic clam settlement.

Since this incident, the plant has installed double shutoff valves on these lines to help isolate the supply headers and coolers when they are in standby mode. During a recent outage, approximately 20 valves were also replaced to further reduce valve leaks.

At another plant, the combination of an open inlet valve and a closed but leaking outlet valve allowed Asiatic clams and silt to deposit in the inlet waterbox of a backup turbine-bearing lube oil heat exchanger. The open inlet valve allowed silt and Asiatic clams to enter the heat exchanger and settle in the waterbox. The leaking outlet valve provided a continuous flow (approximately 4 ℓpm) of fresh water to the Asiatic clams and allowed further deposition of Asiatic clams and silt. The inlet water temperature was approximatley 16°C. The combination of a continuous low-velocity flow of warm service water and the accumulation of silt provided conditions which allowed Asiatic clams to grow. The heat exchanger was in standby condition for approximately 9 months, during which time Asiatic clams and silt accumulated to a depth of 70 to 100 mm (3 to 4 in.). This fouling incident was discovered during a scheduled, visual inspection of the turbine-bearing lube oil heat exchanger. During that inspection, the online turbine-bearing lube oil heat exchanger was found to be completely free of Asiatic clams and silt. Plant personnel speculated that the weekly chlorination (30 minutes at 1 ppm free residual chlorine) was ineffective in controlling the Asiatic clams, which entered in the larval stage and survived in a protective layer of silt.

No specific examples of valve leaks are known to have caused fouling by blue mussels or American oysters. Leaking valves, however, may be a contributing factor to blue mussel and American oyster occurrences in raw-water piping associated with redundant and intermittent-use cooling loops. Leaking valves have been known to allow American oysters to foul intermittent-use heat exchangers in an estuarine plant on Chesapeake Bay.

Plant Operating Transients Affect Flow Patterns

Transients in plant operation cause changes in the flow patterns of raw water and have been known to cause or reveal clogging of heat exchangers by relic shells. Changes in flow patterns occur when: 1) redundant cooling loops are used alternately, 2) intermittent systems are used, 3) the main condensers and circulating-water headers are thermally backwashed, or 4) water hammers are severe enough to cause pressure transients.

Redundant cooling loops are used alternately to perform maintenance and to ensure that all loops receive equal wear. Additionally, other intermittently used systems are operated only during flow tests or during shutdown and in emergencies. The frequency with which these intermittent systems are used affects fouling. Frequent flow testing or flushing may actually provide a more habitable environment for Asiatic clams by providing a more frequent supply of food and oxygen. A notable example of how flow-testing frequency and testing procedures can compound Asiatic clam fouling occurred in the fire protection system of a non-nuclear industrial processing plant. Because of its safety significance at the plant, the fire protection system required frequent flow testing to ensure its operability. Plant specifications called for some fire-system loops to be flow-tested biweekly and others monthly. Flow tests, however, were conducted at a reduced flow rate from that which would be required during design-basis operation of the fire protection system. After several years of operation, the plant changed its flow-test procedures to require testing at the design-flow rate of the fire protection system. The result was severe blockage of fire mains and branch piping due to Asiatic clam clogging. This condition resulted from frequent low-flow tests that allowed Asiatic clams to become established in the piping, and from full-flow tests that carried large amounts of adult Asiatic clams and silt into the fire protection system from the intake bays. Subsequent inspection of the fire-water intake structure revealed accumulations of Asiatic clams and silt up to 1 meter deep near the fire-pump suctions.

Thermal backwashing is used at several coastal plants to control blue mussel growth in raw-water intake structures and piping. At one plant, the initial thermal backwash caused a massive blue mussel kill in the intake structure. 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 RBCCW and TBCCW heat exchangers.

Similar conditions that could result in a large thermal kill of Asiatic clams also exist at freshwater plants where seismically diked cooling ponds are used for the ultimate heat sink (Imbro and Giannelli 1982). If the pond is fed from a water body that contains Asiatic clams, it is likely that Asiatic clams will also be found in the pond. The final safety analysis report (FSAR) from a plant where Asiatic clam fouling has occurred states that the temperature of the cooling pond would reach approximately 50°C (120°F) if a loss of coolant accident (LOCA) were to occur during the summer months. These temperatures would cause near 100% mortality of the Asiatic clam population in the pond. It should also be noted that dead Asiatic clams or blue mussels may have a higher clogging potential than live ones (Imbro and Giannelli 1982). After death, the two shell halves open up (gape), making bivalves more susceptible to being carried with the flow. Also decomposition of the soft tissue causes gases to form, which reduce the specific gravity of bivalves to the point where they may even float. Therefore, prolonged use of the cooling pond during and after an accident could kill Asiatic clams and allow them to clog heat exchangers.

Water hammer can occur when flow in a pipe is stopped suddenly by a fast-acting shutoff valve. This sends a pressure spike back upstream of the valve. One utility reported that reduced heat exchanger performance caused by clogging of heat exchangers with Asiatic clams began to show up soon after a water hammer had occurred. Another plant reported American oyster fouling had occurred in its U-tube, type RHR heat exchangers after a pressure transient. American oysters had built up inside the supply piping to the RHR heat exchangers, and plant personnel indicated that water hammer may have loosened the American oysters and swept their shells into the heat exchangers. The resulting high-pressure differential across the divider plates of the heat-exchangers caused the plates to displace up to 230 mm (9 in.) at the bottom center of the plate. This allowed coolant to bypass the heat exchanger tubes and flow directly from the inlet to the outlet of the heat exchangers, further reducing the heat removal capacity of the heat exchanger tubes.

Component Configurations Affect Flow Patterns

Clogging of heat exchangers with relic Asiatic clam shells has been related to changes in flow configuration in the service-water system. At one plant, fouling became apparent soon after flow was diverted to redundant heat exchangers or to intermittently used cooling loops for flow testing. Asiatic clams that may have grown in the branch lines (both upstream and downstream of the inlet valve) were washed into the heat exchangers and became trapped in the tubes and against the tube sheet.

The inlet side of valves affect flow patterns and provide areas where relic shells have been known to accumulate. X-rays of valves in a seawater piping system showed accumulations of relic shells in the inlet well of the valves (Sergy and Evans 1975). One plant has had persistent American oyster fouling on the upstream side of the inlet valves to their containment-fan cooling units (similar to CCUs). Relic American oyster shells accumulate in the valve inlets and choke off flow to the coolers. These ball valves are equipped with a cavitation control device consisting of a bundle of 13 mm (½ in.) diameter tubes placed directly behind the valve disc (ball). The obstruction caused by the tube bundle acts as a filter for any shells or other debris with a minimum cross-section larger than 13 mm. The plant has determined that the tube bundles are not essential to control cavitation under actual operating conditions, and plant personnel are considering removing them.

Design characteristics that affect flow patterns have caused Asiatic clam fouling to be more severe in one of two adjacent units at a power plant. Intake canal and intake structure design, and the different types of circulating-water systems of each unit, have caused fouling at one plant to be more severe in unit A than in unit B (Figure 13). In this example, Unit B has a once-through circulating water system (condenser cooling provided from the raw-water source), and Unit A has a closed-loop circulating water system (condenser cooling via a natural draft cooling tower). Total flow through the Unit A intake structure during normal operation is approximately 2520 liters per second (ℓps) (40,000 gallons per minute, gpm), whereas flow through the Unit B intake is approximately 31,500 ℓps (500,000 gpm). Due to the wide difference in flow volumes and the sudden widening of the intake canal immediately in front of the Unit A intake, the Unit A intake seems to provide ideal conditions for Asiatic clam settlement and growth. Eddies and backwaters in this area provide low velocity flow conditions where Asiatic clams can settle, and the higher-velocity flow into the Unit B intake provides an abundant supply of dissolved oxygen and nutrients to the Asiatic clams.

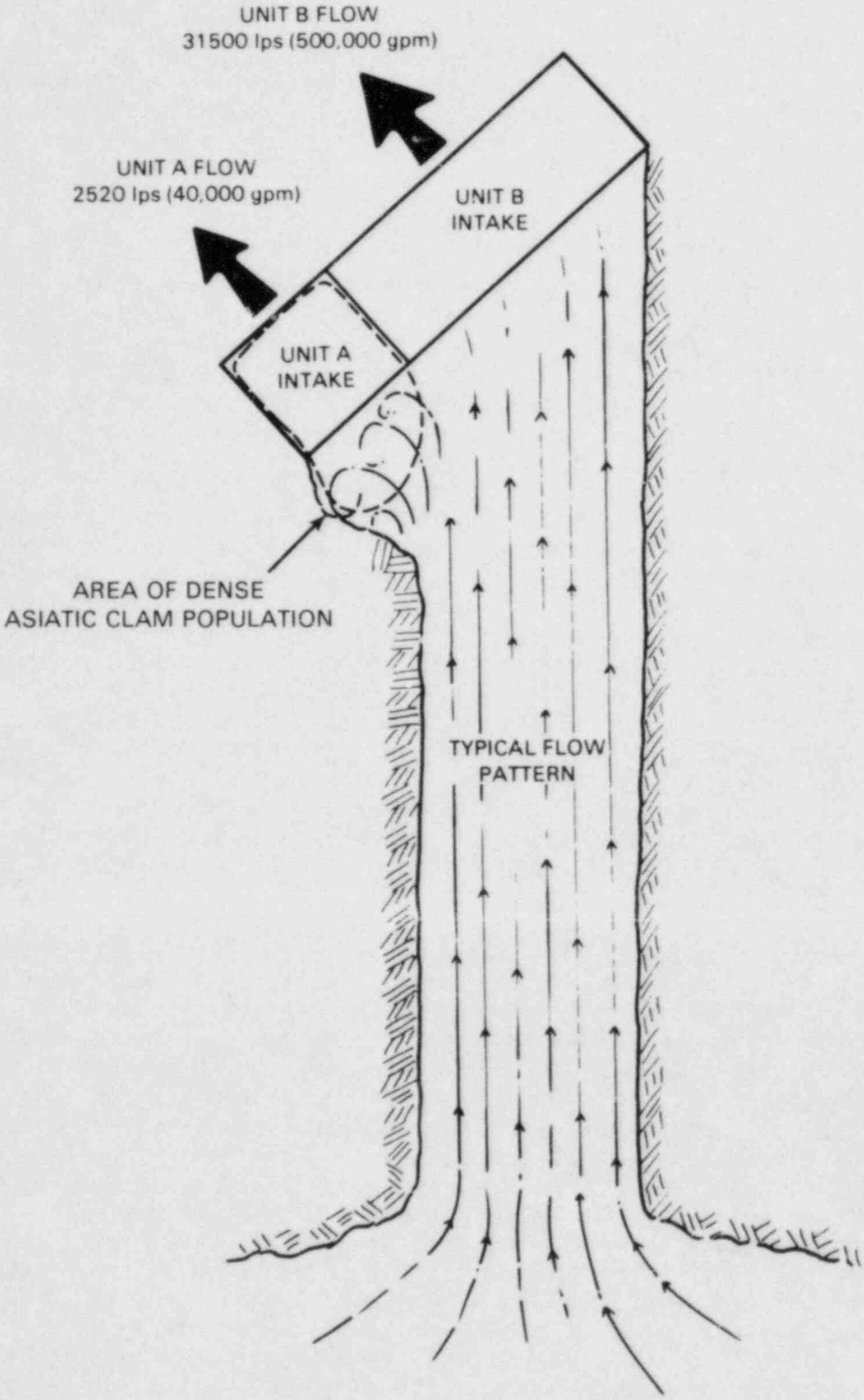

FIGURE 13. Plan View of Intake Canal Showing Typical Flow Patterns and Area of Dense Asiatic Clam Population

Inspections of the Unit A intake bays have shown accumulations of Asiatic clams and silt up to 1 meter (3.3 feet) in depth while similar inspections of the Unit B intake bays showed relatively few Asiatic clams and only small deposits of silt. The high volume, relatively high velocity flow conditions in the Unit B intake do not allow Asiatic clam larvae and silt to settle from the raw-water, whereas the lower volume, low velocity flow conditions in the Unit A intake do allow silt and Asiatic clams to settle. Inspections of the intake canal also show very little silt and few adult Asiatic clams. The flow velocity in the canal is high enough to keep it swept clean of Asiatic clams and silt.

SUITABLE AREAS FOR SETTLEMENT AND GROWTH

Raw-water systems in nuclear power plants provide various areas suitable for bivalve settlement and growth. Suitability is determined by the substrate material itself, by the deposition of materials on the substrate, and by the configuration of the area. Most service-water piping is constructed with metal or concrete; however, low flow areas or "dead areas" provide areas where silt and larvae can accumulate. These silted areas can serve as substrates for bivalves to initially settle and grow. Additionally, pitted surfaces on service-water systems may promote bivalve settlement.

Low velocity flow conditions and silting often occur near geometric discontinuities in raw-water systems where eddies and back water conditions exist. Some locations where low velocity flow conditions typically exist are in service water inlet structures (Figure 14), at inlets to heat exchanger waterboxes, and where there are sudden changes in pipe diameter. Low velocity may also occur in lines with leaking or partially open valves.

Deposition of Silt and Mud

Silt and mud deposits provide a substrate for Asiatic clams, although studies of the Delta-Mendota Canal in California show that Asiatic clams favor gravelly substrates (Eng 1979). Asiatic clams are often found in environments with high silt concentrations, but this may be due primarily to the similar flow requirements for the settlement of each. The presence of silt is, however, a good indication of where Asiatic clam fouling may occur. Several utility personnel indicate that as a general rule, "where you find silt you will also find Asiatic clams."

The presence of silt or other suspended inorganic material inhibits blue mussel growth. Suspended silt can reduce the concentration of planktonic food and decrease the filtering efficiency of blue mussels (Bayne and Widdows 1978). Kastendiek et al. (1981) suspected that increased sediment loads reduced blue mussel growth around the outfall of the San Onofre nuclear plant in southern California.

Like Asiatic clams, American oysters appear to be more tolerant than blue mussel of high silt concentrations. One estuarine plant located at the mouth of a river in Chesapeake Bay has experienced widespread American oyster fouling coupled with high levels of silt in the intake water.

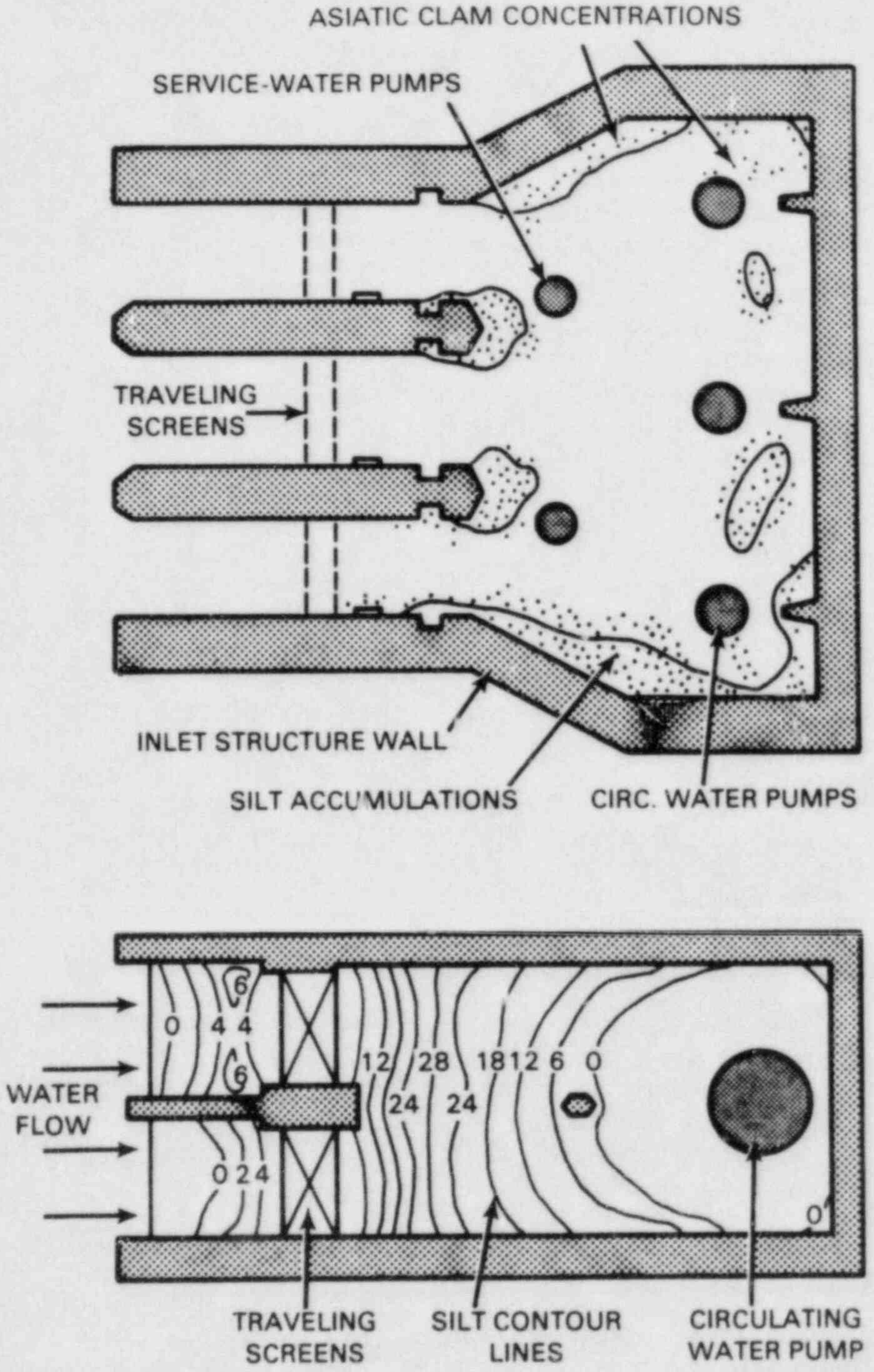

FIGURE 14. Typical Locations Where Silt and Asiatic Clams Deposit in Intake Structures

Corrosion Products

Corrosion is a problem in both freshwater and saltwater plants. Corrosion is caused by accumulations of silt, by the decomposition of organic matter trapped in stagnant piping runs, and by the corrosive nature of saltwater. Two mechanisms that cause corrosion of carbon steel in the presence of silt are electrochemical reactions and the presence of sulfides. Electrochemical corrosion in carbon steel piping results from a nonuniform distribution of dissolved oxygen (Bacon 1978). This renders the area exposed to low oxygen concentration anodic with respect to areas in contact with higher oxygen concentration. Thus, areas where silt has deposited may become oxygen deficient, allowing electrochemical corrosion to occur.

The second mechanism known to cause accelerated pitting corrosion in carbon steel piping is the presence of sulfides. One utility noted that pitting and corrosion in their fire protection system is more prevalent on the bottom inside surface of piping where silt and organic matter deposit. Chemical analysis of the corrosion product revealed the presence of sulfides. Sulfides may have resulted from decomposition of organic matter in the fire protection system.

Corrosion in small carbon steel piping (primarily the accumulation of iron oxide) has been a problem in several freshwater plants. Two utilities noted this and have replaced portions of their small-diameter service-water and fire-protection system piping with stainless steel piping. No further corrosion problems have been reported at these plants.

Silt and other suspended particles are deposited when flow velocities are low. Fluid velocities in municipal water systems are typically kept above 0.9 mps (3.0 fps) to prevent silting. At one freshwater plant where Asiatic clam fouling has occurred, levels of suspended solids in the service water were as high as 10,000 ppm during peak run-off periods. Silting at this plant has been most noticeable in room coolers in the auxiliary building. The room coolers for the high pressure safety injection (HPSI) pumps were the most affected. Other plants have also noted silting in room coolers and other small, intermittent-flow heat exchangers.

Corrosion in saltwater-cooled plants is controlled by using closed-cycle cooling systems, which reduce the number of components that interface directly with saltwater, and by using corrosion resistant materials in those components that do come in contact with saltwater. Heat-exchanger tubes and baffle plates are typically made of a copper-nickel alloy (often 90/10). Some plants, however, are replacing their copper-nickel condenser tubes with titanium tubes to extend tube life. Carbon-steel raw-water supply piping is typically lined with either concrete or rubber. These lining materials may, however, provide equal if not better surfaces for the attachment of blue mussels and American oysters. In a substrate preference study, Butler (1954) observed that American oysters prefer to attach to cement even more than to other American oyster shells.

Other effects of corrosion are reduced flow area and increased surface roughness, both of which restrict the flow capacity of piping. Increased surface roughness, in particular, may provide a more suitable surface for attachment of bivalves and provide a boundary layer that promotes the settlement of both silt and bivalves. Thus, silt, corrosion products, and bivalves all contribute to degraded flow conditions in raw-water systems.

Relative Elevation of Components

Two plants have noted that components at lower elevations foul more readily than those at higher elevations. At one plant, Asiatic clam fouling has occurred in the service-water coils to the containment cooling units (CCUs). This plant has four CCUs, one pair sitting atop the other pair. The bottom CCUs have, in the past, fouled more severely than the top ones. Flow velocity carries Asiatic clams and relic shells along the bottom of the inlet header and into the bottom coolers. Flow velocity is not, however, great enough to carry large numbers of Asiatic clams and relic shells up the vertical header to the upper CCUs. Asiatic clams were found in the upper coolers, but in smaller numbers than in the lower coolers.

Another plant noted that American oyster fouling was most dense in the service-water header and became less dense as the header and branch lines increased in elevation. Gravity may have caused American oysters to settle preferentially at the lower elevations. Another explanation may be that the large number of oysters at the lower elevations depleted oxygen and nutrients to levels that could support only a reduced population in areas farther down the piping.

Low spots in piping and areas with sudden changes in flow direction can act as traps where bivalves and relic shells accumulate. Debris filters have been designed for these areas (MacPhee 1983; Goss and Cain 1976; Drake 1982) and have effectively reduced clogging of heat exchangers.

WATER TEMPERATURES THAT ENHANCE BIVALVE GROWTH

Water temperature is a primary factor determining whether bivalves can survive in the raw-water source or in the raw-water systems at nuclear power plants. Each species can tolerate a specific range of temperatures. Additionally, thermal tolerance limits of bivalves vary with lifestage, previous thermal history, duration of exposure, and the presence or absence of other stresses such as parasites, infections or gas bubble disease, and toxic elements in the water. Bivalves may also show higher than normal mortality rates when exposed to sudden temperature changes. This may even be true at temperatures within the maximum and minimum temperature limits for the species. For example, bivalves acclimated at low temperatures may show high mortality rates when exposed to higher temperatures that are still below the maximum temperature limit for the species.

Thermal Tolerance of Asiatic Clams

Although thermal tolerance limits of Asiatic clams are dependent on acclimation temperature and life stage, the upper limit appears to be between 31° and 35°C, and the lower limit between 2°and 4°C (Mattice et al. 1982). Our survey of plants fouled by Asiatic clams shows that raw-water temperatures range from 0°C in winter to 32°C in late summer. Optimum temperatures for Asiatic clam growth are in the mid-20°C range (Mattice et al. 1982). One utility reported that the water to their turbine-bearing lube oil coolers is approximately 16°C. Water temperatures at the inlets to continuous-flow heat exchangers will be approximately equal to the temperature of the source water. The retention period of water held in systems that are used intermittently may, however, be long enough for the water to reach room temperature (about 20°C).

Thermal Tolerances of Blue Mussels

Water temperatures that support blue mussel growth range from 3° to 25°C. Plants where blue mussels have been a major fouling organism have water temperatures ranging from approximately -1°C in winter to 22°C in late summer.

Thermal Tolerances of American Oysters

Water temperatures that support American oyster growth generally range from 6° to 32°C. Seasonal temperature extremes at plants where American oyster fouling has been a problem are approximately 5.5°C in winter and 30.5°C in late summer.

AVOIDANCE OF POPULATION CONTROLS

Bivalve survival and growth are controlled in raw-water systems by the injection of chemicals to the water and by thermally backwashing the system. Chlorination of raw-water is the most common and most effective means of controlling Asiatic clams, blue mussels, and American oysters. However, if chlorination is not properly scheduled, or if the concentration of free residual chlorine is too low, bivalve populations may not be controlled. Also, mechanically unreliable chlorination systems can effectively halt all chlorination while the system is down for repair. During this downtime, bivalves can enter the raw-water systems and settle in protected areas.

Bivalve populations are controlled naturally by predators such as fish and muskrats. Since these predators cannot enter the raw-water system, bivalves that enter the system are able to thrive.

Chlorination

Chlorination is most effective when it is scheduled to coincide with bivalve spawning, when chlorine concentrations are high enough and of sufficient duration to kill bivalves, and when the chlorination system is reliable.

Chlorination Schedules

Chlorination to control larvae is most effective when scheduled to coincide with spawning seasons (Goss and Cain 1976) and flow testing or flushing. Continuous chlorination at 0.5 to 1.0 ppm residual chlorine for one or two 3-week periods during the spawning season has been shown to control Asiatic clam larvae (B.G. Isom, unpub. manuscript, Tennessee Valley Authority). Although dictated somewhat by environmental conditions (primarily water temperature), spawning periods are greatest in the spring and fall. Continuous chlorination, however, may not be a control option given the current EPA regulations on chlorine discharge from power plants (Mattice et al. 1982). Current regulations assume that the service-water effluent is not dechlorinated before it is returned to the source water.

A southeastern utility has implemented a program for the continuous chlorination of service-water systems during the Asiatic clam spawning seasons. Its studies show that the service-water system must be chlorinated to a total residual chlorine level of 0.6 to 0.8 ppm to adequately control Asiatic clam larvae. The program also calls for the auxiliary cooling-water systems to be chlorinated to the same level for two 3-week periods, corresponding to the beginning and end of the spawning season. During these periods, a small, continuous flow of chlorinated service water is also established through all main fire system headers normally exposed to raw water. This ensures that, when chlorination has been completed, the fire protection system will be filled with chlorinated service-water while the system is in standby condition.

Service-water chlorination should coincide with flow tests of intermittently used systems. Thus, when flow testing is completed, the systems are filled with chlorinated raw water and returned to standby condition. Because the flow of raw water bypasses systems in the standby mode, failure to chlorinate during flow testing effectively means that systems that would benefit most from chlorination may never by chlorinated. After finding Asiatic clams in intermittently used systems, personnel at several plants have implemented such schedules and have reported success in controlling fouling.

Measurement and Maintenance of Lethal Chlorine Levels

Correct measurement of residual chlorine levels is necessary to ensure the effectiveness of a chlorination system. Silt and other suspended particles in a raw-water system have a chemical demand for chlorine; that is, they combine with chlorine in the water to reduce the free chlorine level. This factor makes residual chlorine levels both time and space dependent. Free residual chlorine levels that are measured near the point of injection will be unrealistically high in comparison to levels measured at service-water components further downstream. For this reason, free residual chlorine levels should be measured downstream from all components where bivalve fouling is a potential problem. Several plants have also noted wide variations in chlorine concentration throughout the service-water cooling loops. This may be attributed to poor mixing of chlorine in the intake structure and service-water header.

Reliability of Chlorination Systems

Unreliable chlorination systems can be a major factor in allowing Asiatic clam larvae to become established in raw-water system piping. Although technical specifications call for chlorination at specified times during plant operation, the chlorination system is not "required" for safe operation. Utility personnel indicate that chlorination systems often do not receive the same level of maintenance attention as do systems which are safety related and, thus, more critical to plant operation. As a result, some plants have operated for months with the chlorination system out of service. One fouling incident directly related to an unreliable chlorination system involved American oyster fouling in a saltwater-cooled plant. Severe fouling of the RHR heat exchangers was attributed to the chlorination system being out of service for about 9 months. American oyster shells in the RHR supply headers had formed a layer averaging 5 cm thick. Some areas had a layer of shells as thick as 13 cm. Additionally, loose shells and shell fragments were found wedged in heat exchanger tubes, and some were blocking the tube sheet. Shells were also found in the emergency diesel generator coolers.

Of the six utilities visited during this study, five expressed dissatisfaction with the overall performance of the chlorination systems at their plants. Each of these utilities has at some time experienced bivalve fouling, and several are in the process of upgrading their chlorination systems. Several have started continuous chlorination of their service-water and auxiliary cooling-water systems. In the majority of plants, these chlorination systems were not originally designed to provide continuous chlorination for bivalve control. Design criteria generally called for intermittent chlorination to control slime, algae, and other microfoulants on heat-exchanger surfaces. The result is that many of these plants have chlorination systems that cannot provide continuous chlorination because they are inadequately designed and/or improperly maintained. Common problems include: corrosion of chlorination system components, inadequate or improperly sized hypochlorite metering pumps, uneven distribution of chlorine, and an overall lack of proper system maintenance.

One utility noted a correlation between the reliability of their diaphragm-type chlorination pumps and the injection location of the hypochlorite solution into the service-water system. They noted that chlorination systems which inject hypochlorite solution downstream from the service-water pumps have a higher incidence of pump diaphragm failure than similar pumps in systems where hypochlorite is injected directly into the service-water intake structure. This difference has been attributed to the fact that injection downstream of the service-water pumps requires pumping against a back pressure of approximately 345 kPa (50 psi). This pressure, while not unusual for raw-water systems, is high enough to substantially shorten the operating life of these diaphragm-type injection pumps.

Bivalve Avoidance of Chlorinated Water

A characteristic of bivalves is their ability to "clam-up" in response to environmental stimuli. Bivalves avoid adverse environmental conditions by retreating into their shells and respiring anaerobically for extended periods of time. This behavior allows bivalves to avoid antifoulant control measures such as chlorination. Mattice et al. (1982) reported that chlorine limits set by the U.S. Environmental Protection Agency have proven to be ineffective in controlling Asiatic clam fouling at power plants. They reported Asiatic clams can tolerate target concentrations of 10 mg/L total residual chlorine for up to 30 min. Chlorination practices at Tennessee Valley Authority plants that include continuous chlorination during the Asiatic clam breeding season have been somewhat successful (Goss and Cain 1977). However, residual levels are difficult to maintain in static systems, such as fire protection systems. Burial in silt also provides additional protection from chlorinated water.

Absence of Predators

The absence of predators has been identified as one factor that contributes to the formation of dense populations of Asiatic clams in raw-water intake structures. Because the traveling screens are placed directly in front of the intake water bays, blue catfish, freshwater drum, crayfish, muskrats and other natural predators are not able to enter the intake structure. One utility indicated that predation by fish on early life stages of Asiatic clams appeared to be responsible for low densities of Asiatic clams in their cooling pond. They have postulated that high densities in the intakes prior to Asiatic clam control measures was due, in part, to the traveling screens that provided protection from predatory fish. Although predation may have some affect on the population dynamics of Asiatic clams, the major cause of dense Asiatic clam populations occurring in intake sturctures is thought to be flow velocities and flow patterns that are conducive to Asiatic clam growth.

It is not known whether the lack of predation in the intake structure has a noticeable effect on blue mussel and American oyster fouling. In the plants where these two species have been a problem, these bivalves seem to be dominant species. Thus, the populations of these species may be dense enough so that predation, even in the natural environment, would not preclude fouling problems.

FIRE PROTECTION SYSTEM FOULING

Several of the characteristics previously described also contribute to Asiatic clam fouling in the fire protection system. The most common cause of fouling of the fire protection system appears to be miscellaneous use of the fire system. Several utilities have commented that the fire protection system is routinely used to wash down equipment and clean outside areas. Two utilities also noted that even lawn sprinklers have been found attached to the fire protection system. This misuse of the system generally goes unnoticed because the jockey pumps that maintain system pressure will allow minor flows without tripping the main fire pumps. Miscellaneous use of the fire protection system effectively provides ideal conditions for Asiatic clam fouling. Several plants have noted that fouling of the fire protection system was reduced after the system was flushed and all miscellaneous use of the system ended.

In a previous section, frequent flow testing was linked to severe Asiatic clam fouling in the fire protection system of an industrial processing plant. Flow testing of this fire protection system was conducted biweekly for some fire system branch lines and monthly on others. Flow testing of the fire systems at nuclear plants is typically conducted on an annual or semiannual basis, and does not provide as ideal an environment for long-term Asiatic clam growth, as does the more frequent flow testing described above.

Valve leaks may also affect fire protection system fouling; however, they do not appear to be as severe a problem as they are in the raw-water cooling systems. Globe valves are typically used to control flow at fire hose racks and are not as susceptible to leaks as are butterfly valves. Butterfly valves are typically used in raw-water cooling loops to throttle flow.

Component size is also important to fire protection system fouling, because it can drastically magnify the consequences of even minor Asiatic clam fouling. Many fire system branch lines have piping that is 25 mm (1 in.) or smaller in diameter. Even more critical are the automatic fog and spray systems which typically have flow nozzles that are of 13 mm (1/2 in.) in diameter or smaller. In these systems, only one relic Asiatic clam shell is required to completely block each flow nozzle. In a worst-case scenario, approximately one handful of Asiatic clam shells could completely disarm the fire- protection system in critical areas such as the cable spreading rooms.

BIOFOULING MACROINVERTEBRATES

Responses to IEB 81-03 indicated that Asiatic clams, blue mussles, and American oysters are the macroinvertebrates that most often foul raw-water systems of nuclear power plants. This section describes the biological characteristics of these three bivalves, particularly as they relate to fouling.

ASIATIC CLAM (CORBICULA FLUMINEA)

The Asiatic clam (Corbicula fluminea) is a member of the phylum Mollusca, class Pelecypoda. Pelecypoda are aquatic bivalve mollusks that live in most types of freshwater, especially large rivers (Pennak 1978). Asiatic clams prefer sandy or gravel substrates but are able to tolerate a wide range of substrates such as large cobbles, boulders, and soft silts. Asiatic clam densities in rivers concentrate within 2 to 3 m of the shore. Densities may range from a few per square meter to several thousand per square meter.

Asiatic clams were transported to North America from Asia in the early 20th century (Britton and Morton 1982). Their presence in the United States was first recorded in the Columbia River in 1938 (Burch 1944). Today, virtually every major river system in the United States south of latitude 40° has populations of Asiatic clams (Figure 15).

Life History

The life span for Asiatic clams is about 14 to 17 months, but some individuals can survive up to 24 months. The shells of adult Asiatic clams average about 35 mm in length. Larger individuals have shells as long as 40 mm (Alderidge and McMahon 1978).

Reproduction

Sexually mature Asiatic clams are usually monoecious (i.e., a single individual has both male and female sexual organs at the same time). Eggs and sperm develop in the reproductive organs of the Asiatic clam throughout most of the year. When critical environmental temperatures are reached, sperm are released into the ambient water by the adult. Asiatic clams inhale or pump water into and through their internal organs for feeding and respiration. Sperm in the ambient environment are inhaled. The inhalation of sperm may result in the release of the eggs into internal cavities of the Asiatic clam. Fertilization and early embryonic development occur in these internal cavities (infrabranchial chambers). Development proceeds from the newly fertilized egg to an early juvenile stage within the adult.

During the breeding season, the adult female carries thousands of embryo in various stages of development (Figure 16). The early developmental stages progress from the newly fertilized egg though a cleavage stage to a trochophore larvae. The trochophore larvae stage is common to mollusks and annelids (segmented worms). Trochophore larvae are multicellular,

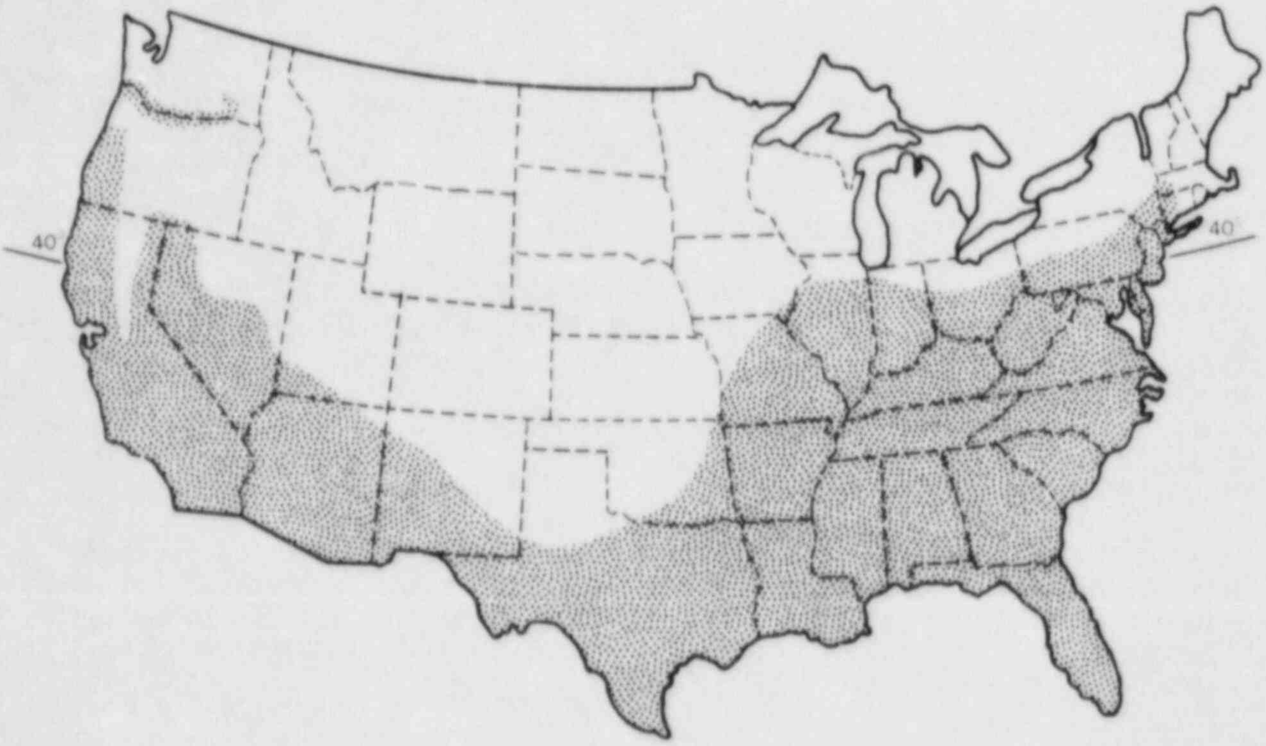

FIGURE 15. Distribution of Asiatic Clams in the Continental United States

cone-shaped, and have cilia. The trochophore, which is about 140 to 220 µm in diameter, develops into a veliger. This larval stage has most of the adult body parts but is distinguished from the adults by a velum. The velum is a ciliated extention of the mantel that aids the veliger in swimming. The veliger soon becomes laterally compressed, develops a shell, and lengthens to 220 to 270 µm. The velum of the veliger is lost and the larvae develops into a juvenile of about 220 µm in length.

Offspring are retained within the adult Asiatic clam from the egg stage to the juvenile stage, at which time they are released into the enviornment. North American Asiatic clams generally release larvae twice a year, usually in the spring and fall. The time of year and frequency of reproduction are dependent on site-specific conditions. Alderidge and McMahon (1978) reported that the reproductive cycle of Asiatic clams in Lake Arlington, Texas, occurred in the spring from late April to late July and again in the fall from late August to late November. Similar reproductive cycles have been reported for populations of Asiatic clams in California (Heinsohn 1958). Biannual spawning has been reported for Asiatic clams in the Delta-Mendota Canal in Northern California (Eng 1979). Some Asiatic clam populations are reported to have single reproductive periods in a year (Villadolid and del Rosario 1930; Sinclair and Isom 1961, 1963). Variation in the reproductive cycle of other bivalves has also been reported (Avolizi 1971; Foster 1932; Heard 1962, 1965; Ladle and Barol 1969; Mackie et al. 1974).

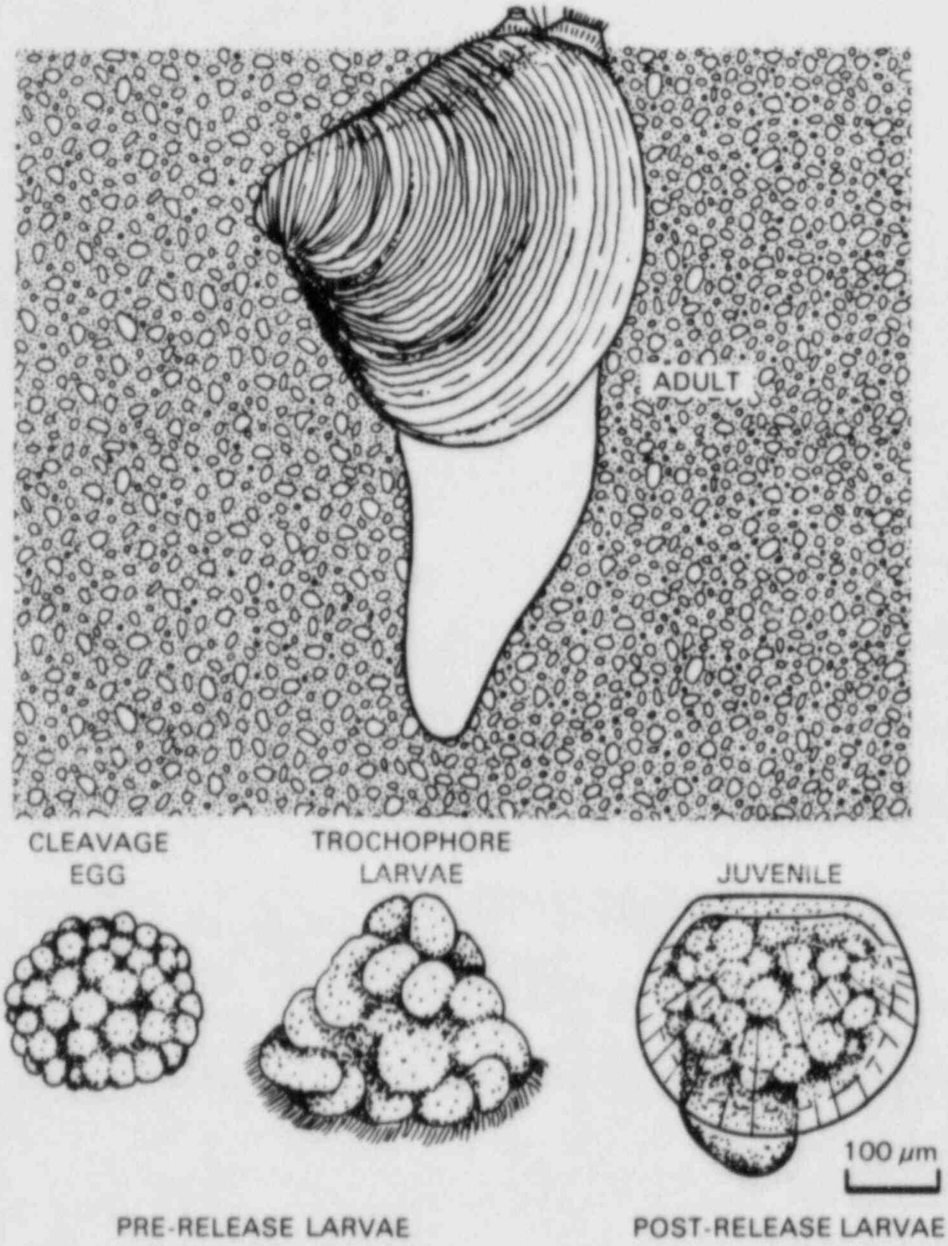

FIGURE 16. Life Stages of the Asiatic Clam

Changes in water temperature usually mark the release of larvae. In Lake Arlington, Texas, the spring spawning period began when water temperatures reached 19°C and ended when temperatures exceeded 32°C. Optimum temperature for juvenile release was 25.7°C (Alderige and McMahon 1978). Fall spawning began when temperatures dropped below 32.5C, and veliger release declined when temperatures dropped below 18°C. The reproductive cycle of Asiatic clams in the Delta-Mendota Canal, California, is also controlled by temperature. Spawning is limited to months (April-October) when water temperatures are above 16°C. Gardner et al. (1976) reported similar observations for Asiatic clams spawning in Georgia.

Fecundity estimates (i.e., the number of young produced by an individual or population of individuals during a specific period of time) vary with population, but estimates of numbers of larvae released range up to 700 per day (Britton and Morton 1982; Aldridge and McMahon 1978; Sickel 1976). Britton and Morton (1982) point out that in a population of 2000 Asiatic clams/m^2, a release of 700 larvae/day represents 1 to 1.5 million larvae/m^2 of adult Asiatic clams. With a 0.1% survival, the population can be replaced within a single spawning season.

Juveniles

Juvenile Asiatic clams grow quickly. A spring juvenile can attain 15 to 18 mm shell length within a few months Britton and Morton (1982). At this size, the Asiatic clam is well within the size range for sexual maturity. Spring-spawned Asiatic clams may contribute to the population fecundity after one season. Because of the decreased water temperatures in winter, the fall-spawned juveniles do not grow as fast as the spring-spawned populations. Most fall-spawned Asiatic clams attain lengths of 10 to 12 mm by spring.

Juvenile Asiatic clam growth has been studied in several river systems. Heinsohn (1958) found that Asiatic clams grew to a length of 15 mm in the first year of growth in California irrigation canals. Sickel (1976) recorded growth to 13 mm in the first year and 21 mm in the second year for Asiatic clams in the Altamaha River in Georgia. As noted above, the Asiatic clam can reach sexual maturity within the first growing season. Aldridge and McMahon (1978) noted that Asiatic clams in Lake Arlington, Texas, reach maturity at 10 mm shell length.

Juvenile Asiatic clams are released from adults when they are about 220 µm in size. They settle near the adult from which they were released unless they are moved downstream by currents. The juveniles are able to move on the substrate by use of the foot.

Settlement and Attachment of Larvae

Adult and juvenile Asiatic clams use a muscular organ, called a foot, to burrow and move. The foot is developed by the time the juvenile is released from the adult. Adults can push the foot into substrates of mud or sand. The protruded foot acts as an anchor while the Asiatic clam opens and closes its shell. The pumping action of the shell and the anchoring property of the foot result in a burrowing motion that eventually buries the Asiatic clam. For the juvenile, the use of the foot for horizontal movement is more important than its use for digging. Rates of movement vary depending on substrate, water temperature, flow, and other environmental conditions (Britton and Morton 1982).

Asiatic clams are also moved by currents if they are not attached or burrowed into the substrate. Depending on the environment, juveniles may be benthic or planktonic. Heinsohn (1958) reported that the juvenile stage is reached before the young are released from the adults and that release of veliger or trochophore larvae represented aborted broods. Sinclair and Isom (1963) found veligers were being released but were functionally benthic. Sinclair (1971) reported that veligers were released and described them as free-living but noted that they became benthic within 48 hours. Eng (1979) noted that both pediveliger and "very early juveniles" are released into the Delta-Mendota Canal. Delta-Mendota larvae populations are transported away from adult populations by currents.

After the young Asiatic clam establishes itself in a suitable habitat, it uses a sticky mucus produced by the foot (the byssal gland) to secure itself to the substrate. The byssal gland secretes a liquid thread onto the substrate. The setting of several threads produces a byssus (anchor) which helps keep the Asiatic clam on the substrate. The byssus is maintained for up to 1 year. If a juvenile Asiatic clam becomes dislodged from a substrate, however, the old byssus can be detached and a new byssus laid down.

Asiatic clams can attach themselves to almost any available substrate. Therefore juveniles that invade a service-water system and find a place for attachment or burrowing can grow, mature, and propogate within the system as long as conditions remain favorable.

Asiatic clams lose their ability to attach to surfaces soon after the 5-mm stage, after which flow velocity becomes a factor influencing their movement. Low-velocity flow allows Asiatic clams to settle and also allows the deposition of suspended particles such as silt. Silt deposits provide a burrowing substrate for Asiatic clams.

Flow patterns may also be an important factor affecting Asiatic clam fouling. Flow patterns in adjacent areas of high- and low-velocity flow provide a good environment for larvae settlement plus a continuous supply of food and oxygen for Asiatic clam growth. Several power plant operators have noted that their intake structures seem to provide ideal conditions for Asiatic clam growth. One plant in particular has noted that the population of adult Asiatic clams in and around the immediate vicinity of the intake is much denser than the average population in the water source. Biologists at these power plants indicate that Asiatic clam larvae are present throughout the waterbody, but that conditions conducive to their growth do not generally exist in the waterbody. Although lack of predators inside the intake structure may contribute to the dense population there, the biologists believe that the unique flow patterns near the intake structure are the major characteristic that has affected population growth. Intake structures have several areas where flow patterns enhance the settlement of silt and juvenile Asiatic clams (see Figure 14).

Physiological and Behavorial Characteristics

Animals have distinct physiological and behavioral traits or characteristics that enable them to adapt to their environment. Some of these characteristics allow Asiatic clams to foul service-water systems. A more detailed discussion correlating biological characteristics with the design of service-water systems is provided in later sections of this chapter.

Substrate Preference

Asiatic clams prefer sandy or gravel substrates, but they are also found in larger rock or in mud or silt (Britton 1982). Asiatic clams densities vary with the type of substrate in a waterbody. Sickle (1976) observed that Asiatic clams from the Altamaha River, Georgia, preferred substrates of fine sand, course sand, and mud, in that order. He also noted that these Asiatic clams would not settle on concrete.

Eng (1979) noted that Asiatic clam populations were most dense in the thin biological incrustations of the concrete linings of the Delta-Mendota Canal or in disjunct sediment bars on the canal bottom. The encrustment provides a suitable habitat and is rich in nutrients, so rapid growth is attained. The rapidly growing Asiatic clams soon outgrow their habitat because the encrustment is shallow. Larger Asiatic clams are therefore detached by the currents within the canal and washed downstream. This displacement leaves a suitable habitat for recruitment of more juveniles.

Factors Affecting Growth

Temperature and nutrients are probably the two most important environmental factors that control growth. Water temperatures in the rivers systems in which they are found range from winter lows of near freezing to summer highs of greater than 30°C. Asiatic clams can tolerate brief periods of dessication; brief, sudden changes in salinity; and brief hypoxic conditions.

Asiatic clams can tolerate a wide range of water temperatures. Mattice and Dye (1976) reported that, for continuous exposures, the upper tolerance limit for 50% of the Asiatic clams tested was between 24° and 34°C when acclimation temperatures ranged from 5° to 30°C. Lower tolerance limits were between 2° and 12°C for acclimation temperatures ranging from 15° to 30°C. Goss et al. (1979) reported similar tolerances and noted that variation was dependant on acclimation temperature and size of the Asiatic clams.

Growth of Asiatic clams from the Columbia River, Washington, has been correlated with plankton levels and water temperatures (Dauble et al. 1983).

Asiatic clams from three size groups averaging 12 mm, 20 mm, and 28 mm were cultured at 10°, 20°, and 30°C during periods of low plankton density (about 300 cells/ml) and at high density (greater that 1000 cells/ml). During periods of high plankton densities, growth occurred for all groups at all temperatures. Growth was significantly greater for small Asiatic clams and least for large Asiatic clams. During periods of low plankton densities, growth was reduced for Asiatic clams at 10° and 20°C. At 30°C, small Asiatic clams did not survive low plankton densities and medium and large Asiatic clams lost weight.

BLUE MUSSEL (MYTILUS EDULIS)

The common blue mussel, a bivalve mollusk of the family Mytilidae, has a circumpolar, boreal, and temperature distribution (Figure 17) in both the northern and southern hemispheres (Seed 1976). In North America, it ranges from Greenland to the Carolinas in the Atlantic, and from Alaska to Baja California in the Pacific (Wells and Gray 1960; Woods Hole Oceanographic Institution 1952). The blue mussel is generally found intertidally or in the shallow sublittoral zone, usually in waters protected from severe wave action (Harger 1972). Blue mussels attach to hard substrates by byssal threads and may form extensive mats or beds that harbor numerous, associated organisms.

Life History

Blue mussels can sexually mature in their first year. Prior to the release of eggs and sperm (gametes), the blue mussel undergoes a succession of developments that begins with the storage of nutrients needed for the reproductive effort, and proceeds through sperm and egg production (gametogenesis) to spawning.

Reproduction

In the northern hemisphere, blue mussels generally spawn in the spring and summer (Seed, 1976). Spawning periods for a blue mussel population may last from 3 to 4 weeks (Chipperfield 1953) to as long as 6 months in asynchronous spawning populations (Seed 1969a). Some populations have more than one spawning period in a single season, and some populations may not spawn at all. Early spawning records in Europe and North America show considerable variation in spawning times (Chipperfield 1953). Seed (1969a) suggests that blue mussels from more southernly European waters spawn later than those from northern regions, and that intertidal blue mussels spawn before sublittoral blue mussels. Seed (1969a) also suggested that reproductive cycles can vary from habitat to habitat in a particular region, and annually within a habitat. Newell et al. (1982) reported that blue mussels along the east coast of the United States generally spawned in summer, but reported no correlation of spawning with latitude and temperature. In fact, two populations at the same latitude at Long Island, New York, had reproductive cycles that were 3 months out of phase; one population at Stony Brook had gonads in peak reproductive condition in April and May, and another at Shinnecock had gonads in peak condition between July

FIGURE 17. Distribution of Blue Mussels in the Continental United States

and October. Other locations from Maine to Delaware varied widely in the timing of the reproductive cycle, and one population in Rhode Island had no reproductive maximum during the summer.

Factors that induce or otherwise influence gonad development and spawning have been the subject of much debate. Temperature and nutrition have probably received the most attention. Seed (1976) briefly reviewed these and other factors, such as mechanical stimulation, lunar cycles, and neurosecretion, and noted a confusing array of opinions. However, in laboratory experiments where reproductive cycles have been observed in blue mussels subjected to various stresses, results strongly indicate that factors affecting reproduction are interactive (Gabbott and Bayne 1973; Vahl 1973; Thompson et al. 1974; Bayne 1975; Bayne et al. 1975; Myint and Tyler 1982). As mentioned previously, adequate nutrition is needed to build energy reserves for body maintenance and gametogenesis, and, of course, it is necessary for growth. Nutrition and temperature are important in determining the cycle of reproduction. In the laboratory, blue mussels and other bivalves can be maintained at a particular reproductive stage by controlling only temperature and food. Temperature often acts as a trigger for gametogenesis and spawning, nutrition and food serve to synchronize events, and neurosecretion actually controls gametogenesis.

'Scope for growth,' the difference between assimilated food (measured in calories) and the energy lost in respiration, is an index of energy balance that can be used to determine the amount of energy available for reproduction and growth (Bayne et al. 1975). Blue mussels subjected to various combinations of nutritive and temperature stress have a strong physiological impetus for reproduction. Severe variations in the normal temperature/nutrition cycle may alter the physiological steady-state of the blue mussel to the point where there is a lack of gametogenesis or a resorption of gametes.

The correlation between phases of the blue mussel reproductive cycle and water temperature varies with the blue mussel population. Chipperfield (1953) noted that the temperature at which blue mussels in Britian spawned was 10° to 20°C. Engle and Loosanoff (1944) observed that blue mussels along the Atlantic coast of the United States spawn when the temperature reached 60°F (15.5°C), although 15° to 16°C can impair gamete production if it is outside the blue mussel's normal seasonal temperature (Gabbott and Bayne 1973; Bayne et al. 1975; Bayne 1975). Moore and Reish (1969) studied gametogenesis in blue mussels in Alamitos Bay in southern California and determined that the peak of the reproductive period was in fall and early winter when the water temperature fell from between 20° to 21°C in September to 13°C in December. This is the reverse of the reproductive cycle in cooler British waters, and it indicates that temperatures above 20°C may suppress reproduction. Egg production in particular was influenced by temperature. The authors also noticed slight variations in the reproductive cycle around the bay, which supports Seed's (1969a) suggestion that reproduction can vary within a habitat. Wells and Gray (1960) contend that the southern limit for blue mussel reproduction on the east coast of the United States is just north of Cape Hatteras, where the water temperature ranges from 8° to 25°C. South of Cape Hatteras, where the water varies seasonally from 15° to 30°C, blue mussels die in the summer before they can reproduce. Blue mussels here appear to be recruited from larvae that are carried to coastal waters south of Cape Hatteras by periodic storms that mix waters of the two biogeographic subprovinces during the reproductive period of the northern blue mussels. The authors report two settlement periods north of Cape Hatteras, late spring and late fall. Myint and Tyler (1982) found that gametogenesis is suppressed at low temperatures (-1.5°C) in both males and females. Eggs were produced and resorbed; sperm were produced but few mature sperm developed. Gametogenesis returned to normal when the temperature was raised to ambient (18°C). Bayne (1965) also found that spawning could be delayed by low temperatures.

Myint and Tyler (1982) also examined the effect of heavy metals on gonad development. They found that copper was more toxic than zinc and zinc was more toxic than cadmium. Copper and zinc (50 ppb and 200 ppb, respectively) inhibited gamete growth and caused lysis of mature gametes. Cadmium (50 ppb) suppressed gonadal development only in early developmental stages. The extent of damage varied with the temperature.

Development and Settlement of Larvae

After spawning and fertilization, the egg undergoes cell cleavage to form a ciliated, free-swimming blastula (Figure 18). The blastula gastrulates and the trochophore larva is formed. A shell gland then develops, which secretes the first larval shell, the prodissoconch I. Additional cilia appear, the vellum is formed, and the larva enters the veliconch or straight-hinge stage. As the veliconch grows, the velum and associated structures differentiate, and the prodissoconch II shell is secreted. Eye spots then appear and a foot develops. This is the pediveliger. Larvae range in length from 90 μm at the straight-hinge stage to a maximum of 305 μm just prior to metamorphosis (Chanley and Andrews 1971).

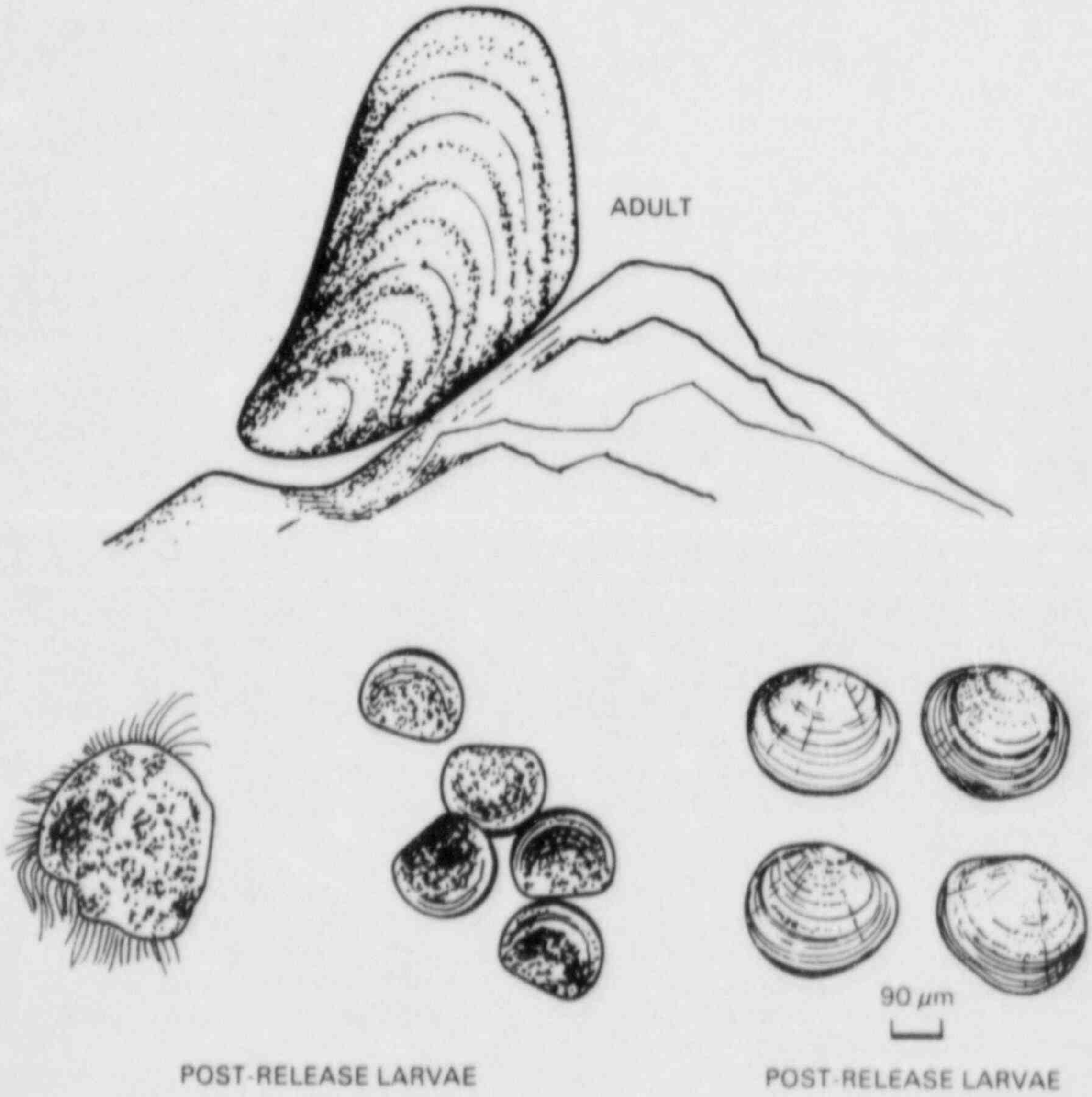

FIGURE 18. Life-History Stages of the Blue Mussel

Early embryos of blue mussels are intolerant of environmental changes. The trochophore of blue mussels acclimated to salinities between 29° and 34°C and to temperatures of 8° to 18°C developed only at or near these ranges (Bayne 1965). There was no cleavage at 5° or 20°C.

Bayne (1965) determined the effects of temperature, nutrition, and salinity on growth of the pediveliger. Using blue mussels that normally live at temperatures of 8° to 18°C, he found that larvae did not feed or develop at 5°C. Between 10° and 13°C, the growth rate increased substantially but slowed gradually as the temperature was raised. At 17°C the growth rate of larvae from a subtidal population of blue mussels decreased, and that from a littoral population leveled off, probably because adults of the latter were normally warmed by sunlight at low tide. He also found that larvae can survive long periods (26 or more days) without food, which may be an advantage when phytoplankton is patchy. Pediveligers from highly saline waters (30°/₀₀ and above) grew only at those concentrations, whereas those from lower salinities tolerated wider ranges. Temperature can also influence the tolerance range; larvae at 16°C grew at a wider range of salinities than did larvae at 13°C.

Early larvae are free swimming. The pediveliger, though, after a planktonic period, settles and crawls, and when a suitable substrate is found, it attaches and metamorphoses into a plantigrade larva. The substrate, to be suitable, must be filamentous, such as a hydroid or a filamentous algae (De Blok and Geelen 1958; Bayne 1964). Settlement is best on clean, unsilted objects of small diameter that have small bumps, grooves, or notches. If a filimentous substrate is not found, then attachment and metamorphoses will be delayed (Bayne 1965) and the larvae will continue to swim and crawl. If metamorphoses is delayed too long, however, then the larvae will assume a crawling rather than a swimming locomotion. Temperature can affect the duration of delay. Delay was 43 to 46 days at 10° to 11°C and 2 days at 21° to 22°C. At higher temperatures, delay did not occur. However, the major factor that influences the delay of metamorphoses is the availability of the proper substrate, and temperature only determines the maximum amount of time delay that can occur. This delay greatly enhances the probability that the larvae will encounter a suitable substrate.

After settlement and metamorphoses, the plantigrade secretes a byssus which it uses for attachment. This settlement, however, is only temporary (De Blok and Geelen 1958). Bayne (1964) calls it the primary settlement. The larvae appear to outgrow the filamentous material and again become planktonic. This planktonic period may last from 18 days (De Blok and Geelen 1958) to more than 30 days (Bayne 1964) or, under special environmental conditions, may not occur at all or may last almost a full year (Seed 1976). The plantigrade then settles again (secondary settlement), this time on solid substrates or in established blue mussel beds.

Blue mussels are more likely to settle on rough substrates than smooth ones, provided the substrate is not fouled with soft organisms, detritus, or sediments (Geesteranus 1942; Chipperfield 1953). Established blue mussel.

beds tend to offer favorably textured surfaces, because the shells of older blue mussels have lost their smooth periostracum. If settlement is too heavy, though, the blue mussels may smother. For this reason, Theisen (1972) suggests that young blue mussels are able to use their foot to clean their shells and prevent the attachment of larvae.

Blue mussels are gregarious (Seed 1976). Their attachment to each other and to a substrate offers mutual support against waves, currents, and other disturbances. Blue mussels, especially young ones, can detach themselves and move around. They often tend to form clusters. Maas Geesteranus (1942) and Seed (1969b) observed that the attraction is not chemical, but thigmotropic; that is, blue mussels favor discontinuities in the surfaces to which they attach.

Adult blue mussels subjected to sublethal thermal stress may produce abnormal larvae. Adults that are fed low rations and kept at temperatures higher than their acclimation temperature produced eggs with abnormal cleavages, abnormal trochophores, and fewer-than-normal prodissoconch larvae (Bayne 1972). Larvae seemed particularly vulnerable to stress during periods when new tissues and organs were being formed. Bayne et al. (1975) noticed that growth of larvae from adults that had received a 10°C temperature shock grew more slowly than blue mussels that had not been thermally shocked.

Brenko and Calabrese (1969) investigated the combined affects of temperature and salinity on blue mussel larvae from Milford, Connecticut. Results showed that survival and growth were good at 15°C in salinities from 25 to 35°/oo, and best at 20°C in water 20 to 35°/oo. Outside these ranges, optimal growth and finally survival are reduced.

The Byssus

Byssal threads are the means by which blue mussels anchor themselves to a substrate. The thread consists of an adhesive disk that cements to a substrate, a cylindrical filament that moors the blue mussel to the disk, and an attachment ring which holds the thread to the animal. The thread is formed in a groove on the foot.

Numerous physical and environmental variables can affect byssal production and quality. The diameter of the thread increases and the number of threads produced per unit time decreases with the size of the animal (Allen et al. 1976). This occurs in part because small blue mussels tend to move about more often than larger blue mussels, so they also break their threads more often.

The number of threads produced may also be affected by salinity and temperature. Allen et al. (1976) observed that the maximum number of threads secreted per day occurred at a salinity of 33.9°/oo. At 8.5°/oo salinity, few if any threads were produced. Van Winkle (1970) reported no production at 16°/oo, in contrast to the findings of Glaus (1968) and Allen et al. (1976). Van Winkle's results may have been influenced by the fact that the blue mussels he used in his laboratory experiments were collected from an area where they were acclimated to 32°/₀₀ salinity and lived near or at their upper lethal temperature (about 27°C). Nevertheless, he did determine that thread formation was reduced above 23°C and was negligible at 26°C. Pearce (1969) reported that the byssus of attached blue mussels weakened at 24°C and did not pull the blue mussels securely down against the substrate. Gonzalez and Yevich (1976) also observed both in the laboratory and in a power plant effluent that the byssus weakened at high temperatures.

Price (1982) states that wave action is a major factor that decreases byssal strength. She also found that attachment was strongest in September and weakest in May (Price 1980). Pesticides can also reduce byssal attachment. Roberts et al. (1975) reported that in 24 hours, 1.0 mg/1 Endosulfan (an organochlorine) will reduce the number of attached blue mussels by 80%, and 0.45 mg/1 will reduce them by 50%.

Succession in Blue Mussel Bed Formation

An established blue mussel bed is usually considered to be a climax community, a community that will maintain its long-term integrity and stability. The question arises whether organisms that usually precede the blue mussel community are necessary for its final development. The first organisms to inhabit the surface of a clean substrate immersed in seawater are bacteria. Kirchman and Mitchell (1981) contend that these bacteria form a thin film and secrete extracellular polysaccharids that are necessary for the attachment of other fouling organisms, or perhaps the entire fouling community. They maintain that the larvae of fouling organisms produce lectins that bind specifically to lectin receptors located on the carbohydrates of the bacteria.

Scheer (1945), studying the development of fouling communities in Newport Harbor, California, noted that the bacterial film proceeded settlements of algae, bryozoan, and blue mussels, in that order. He considered this to be a true succession rather than seasonal progression, since at least the algae and the bryozoans appeared to be reproducing all year. Scheer (1945) suggested that the bryozoans offered more favorable conditions for blue mussel settlement. Reish (1964a), however, studied a blue mussel community in Alamitos Bay, California, and noted that if a new substrate were available at the time of blue mussel spawning and settlement, then blue mussels would be the primary colonizer. If the substrate was immersed outside the Mytilus reproductive period, then other organisms would act as primary settlers. He considered this to be seasonal progression rather than true serial succession.

Factors Affecting Growth

Blue mussel growth is usually expressed as an increase in shell size with time. The shell is used as a measure of growth because it is such an outstanding feature of the blue mussel and is easily measured. Growth rates of blue mussels are highly variable, not only between groups or populations, but even in blue mussels grown under apparently similar environmental conditions (Seed 1976; Stromgren 1976a). Therefore, the growth rate of any one population in a particular habitat is almost impossible to measure (Seed 1969b).

Under ideal conditions, blue mussels may grow more than 60 mm per year. [Reish (1964a) recorded a growth rate of 9 mm per month in southern California.] Under unfavorable conditions, however, blue mussels may grow no more than 20 to 30 mm in 20 years (Seed 1976), which also indicates blue mussel longevity. Blue mussels can live for more than 20 years (Seed 1969b). Growth generally slows with age and is most rapid between the first and fourth or fifth year (Seed 1969b; Almada-Villela et al. 1982). Seed (1969b) stated that reduced growth with age may be due to lower metabolic rates in older blue mussels or to the greater amount of body mass that must be maintained relative to length. Vahl (1973), however, discovered that metabolism does increase with size, and that it increases faster than the pumping rate, resulting in somewhat more limited pumping in larger blue mussels. This affects the filtration rate (the volume of water that a blue mussel clears of particles in 1 hour), and therefore the feeding rate, which Thompson and Bayne (1976) found decreases with increasing size. The limitation in an older animal's ability to transport water may, in the end, determine its final size (Jorgensen 1976). Slow growing blue mussels, though, tend to live longer than fast growing blue mussels (Jorgensen 1976).

Water temperature is a major influence on growth. Almada-Villela et al. (1982) demonstrated that blue mussels acclimated to 10°C had a steady logarithmic increase in growth between 3° and 20°C and a sharp decline beginning at 21°C. Over the long term, however, blue mussels can partly adapt to 25°C so that growth will equal that at 10°C. In the northern latitudes where winter and summer water temperatures can be substantially different, blue mussels may grow seasonally and produce seasonal growth rings that can indicate age reliably. Seed (1969b) found that 90% of the growth of some blue mussels in Britain occurred between April and September. Slow growth during fall and winter may have been due to a combination of low temperature, reduced food, and the storage of food reserves for gonadal development at the expense of shell growth. In lower latitudes where seasonal differences are more uniform, blue mussels may not form growth rings, and in habitats where local conditions vary frequently, blue mussels may produce several growth rings in a year (Seed 1969b). Intertidal blue mussels grow more slowly than subtidal blue mussels because food is not available when the blue mussels are exposed to the air (Seed 1969b; Theisen 1973), and growth may approach zero when the blue mussels remain exposed 50% the time (Jorgensen 1976).

Heated powerplant effluent waters may stimulate growth (Wolfson 1974; Gonzalez and Yevich 1976; Young and Frame 1976). Gonzalez and Yevich (1976), investigating blue mussels in the intake and effluent of a powerplant with an approximate increase in temperature between the two canals of 8°C, found that from March to June blue mussels grew 0.82 mm per week in the intake and 2.0 mm per week in the heated discharge. During the summer the effluent temperature became stressful and finally lethal, so that growth slowed and then ceased. Wolfson (1974), studying a 3°C rise in temperature in a simulated powerplant intake and discharge, also noticed that blue mussels grew faster in the heated water during spring but more slowly during summer. In addition, he found that in a discharge where the temperature alternated every 6 hours between ambient and the 3°C increase, the blue mussels at the end of 1 year were larger than those in a constant 3°C increase, presumably because of better growth in the alternating discharge during summer when the constant high temperature was stressful. However, Almada-Villela et al. (1982) also observed that fluctuating water temperatures tend to improve growth. Growth is not only suppressed at high temperatures, but at low temperatures as well. Theisen (1973) reported that blue mussels in Greenland had slower growth rates than blue mussels found in temperate latitudes. He also reported that growth ceased at 0°C.

Environmental conditions other than temperature that can affect growth are salinity, light, currents, competition for space and food, suspended silt, genetics, and parasites (Seed 1969b, 1976; Theisen 1973). Low salinity retards growth. At the lowest salinity at which blue mussels can exist (4 to $5^{\circ}/_{\circ\circ}$), blue mussels have been observed to reach only 30 to 40 mm shell lengths (Theisen 1973; Seed 1976).

Blue mussels grow faster in constant darkness than in constant light (Seed 1969b; Stromgren 1976a), but as a result, their shells are thinner and have less of the typical blue-black pigmentation. Blue mussels grown in light develop darker, more opaque shells, which is probably a protective adaptation (Seed 1969b). Growth has a diurnal rhythm and is greatest during daylight hours, even in total darkness. Some darkness may be necessary for rapid growth (Stromgren 1976a). Even low light intensity can increase growth. Irradiance of <4 Watts/square meter (W/m^2) may increase growth, whereas there is no response between 5.5 and 10 W/m^2 (Stromgren 1976b). Wavelength is also important. Blue, green, and especially yellow light (600 to 700 nm) increase growth rates, but red light inhibits growth. In full spectrum daylight with high irradiance of long duration, the long wave lengths may override the positive effects of the shorter wave lengths and slow the rate of growth (Stromgren 1976b).

Currents can affect the food supply (Thiesen 1973). If there is little or no current, blue mussels may remove food faster than it can be replaced, possibly reducing growth (Hildreth 1976). Crowding can create competition for food and space, especially where small blue mussels grow among larger blue mussels (Seed 1969b). Suspended silt can decrease clearance rates, which will dilute the organic matter of suspended particles and reduce the absorption efficiency of the blue mussel (Bayne and Widdows 1978). Kastendiek et al. (1981) suspected that increased sediment loads reduced blue mussel growth around the outfall of the San Onofre Nuclear Generating Station in southern California.

AMERICAN OYSTER (CRASSOSTREA VIRGINICA)

The American oyster, *Crassostrea virginica*, is a bivalve mollusk of the family Ostreidae. The American oyster is common to the eastern seaboard of North America (Figure 19) and ranges from northern New Brunswick, south along the Eastern and Gulf Coasts to Mexico and is also found in parts of the West Indies (MacKenzie 1975). American oysters inhabit both the littoral and sublittoral zones to a depth of 130 feet (Merrill and Boss 1966). American

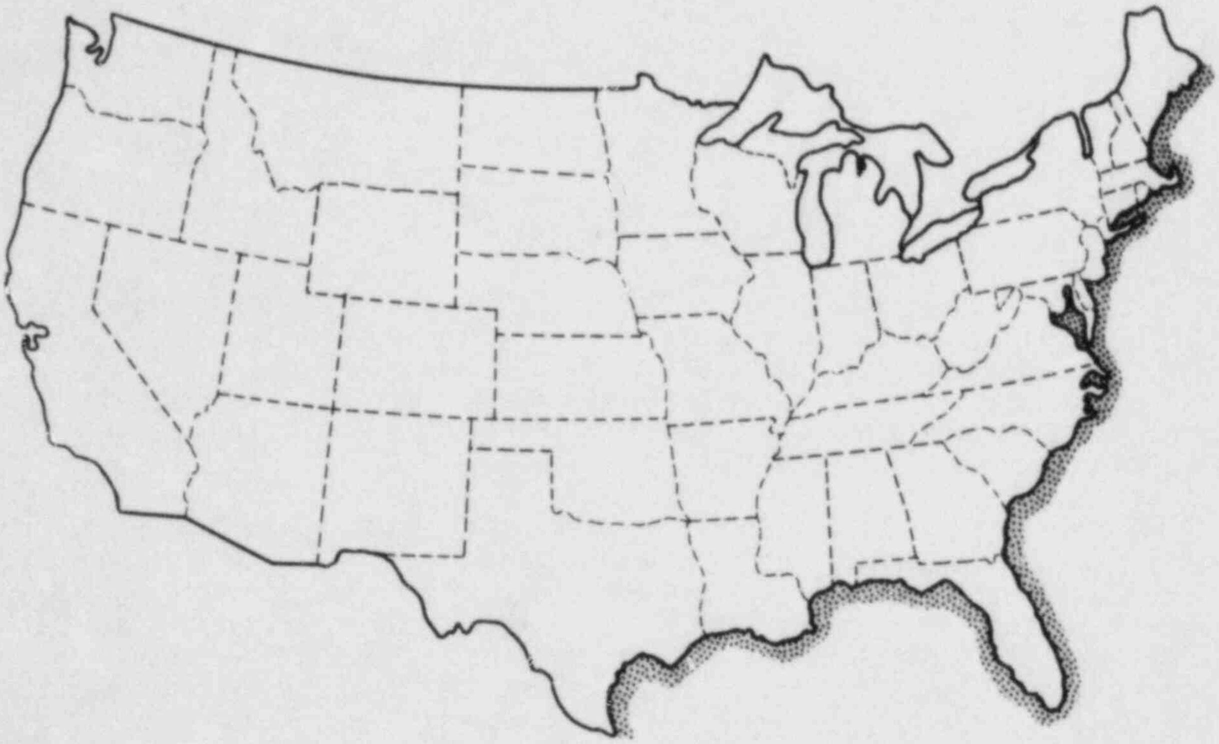

FIGURE 19. Distribution of the American Oyster in the Continental United States

oysters are gregarious and form massive beds or reefs. Shells serve as a substrate for live American oysters (Galtsoff 1964; Gunter 1979). American oysters also attach to other hard surfaces such as buoys and bulkheads, and can be a fouling problem on submerged structures of power plants.

Life History

American oysters may mature sexually during their first year. They can live as long as 40 years and grow to over 20 cm in shell length.

Reproduction

American oysters generally spawn during warm seasons. Spawning times and duration vary with latitude. The first-year class of American oysters are all male, but American oysters are protandrous, and enough individuals subsequently change into females that the sex ratio approaches one-to-one in older American oysters.

The sex of an American oyster may change several times during its life (Galtsoff 1957, 1964; Loosanoff 1965). Like other bivalves that reproduce seasonally, the gonad of the American oyster undergoes an annual cycle of events that culminates in the production of mature eggs and sperm that are released into the surrounding water.

The gonad consists of two lobes, which lie beneath the mantle and merge at maturity on the dorsal and ventral sides to envelop the visceral mass. During the cold season, especially in the northern latitudes, the gonads are in an inactive state (during hibernation of the animal) and the gonad follicles are few in number. Although the gonadal cycle has not been divided into descriptive stages as it has in the blue mussel, the continuum of events is very similar to that of blue mussel gametogenesis.

Gamete proliferation begins in late May or June in American oysters in Canada, early April in Long Island Sound, and as early as February in the Gulf of Mexico (Loosanoff 1942; Ingle 1951; Kennedy and Battle 1964; Hayes and Menzel 1981). Initiation of gametogenesis is a function of water temperature. Loosanoff and Davis (1958) found that 8°C will bring American oysters in Long Island Sound out of hybernation. South of Long Island where the water is warmer, American oysters come out of hybernation at higher temperatures (Hayes and Menzel 1981). Females, depending on their size and health, may produce more than 85 million eggs in a spawning season (Davis and Chanley 1955).

The time required for maturation of the gonad varies somewhat with latitude and is probably dependent on the rate of temperature increase. American oysters from the northeastern United States and Canada usually take many weeks to develop ripe gametes (Loosanoff 1942; Kennedy and Battle 1964). Those from the Gulf of Mexico may take only 4 weeks (Ingle 1951). Loosanoff and Davis (1958), investigating the effect of constant temperature on American Oysters in Long Island Sound found that even though 8°C brought them out of hibernation, an increase to 10°C was still too low for full gonad development. At 15°, 20°, 25°, and 30°C, however, the average time required for 50% of the American oysters to develop ripe gametes was 26.5, 7.9, 5.4, and 4.9 days, respectively. For American oysters south of Long Island Sound, the development times at the above temperatures are longer. For example, gonads from American oysters in New Jersey took an average of 22 days at 27°C to reach maturity (Loosanoff and Davis 1963). The threshold temperature for the initiation of gametogenesis also increases as one goes south. With careful manipulations of water temperatures and a few other parameters in the laboratory, Loosanoff and Davis (1963) have shown that American oysters and other bivalves can be conditioned to develop gametes at any desired rate at any time of the year.

Another factor that can influence gamete maturation is available food. Bahr and Hillman (1967) observed that when food is limited, gonad development is retarded, probably because stored glycogen ordinarily used to supply energy for gametogenesis is used instead to maintain normal metabolism.

Spawning times and duration also vary with latitude and are controlled by temperature. Spawning may last as short as 2 months in Canada to as long as 6 months in the Gulf of Mexico. Spawning seasons at various regions of the American oyster's range are listed in Table 1.

TABLE 1. Spawning Seasons for the American Oyster, Crassostrea virginica, in Seven Locations on the Atlantic Coast of North America

Location	Spawning Duration	Reference
Canada	late June to late August	Kennedy and Battle (1964)
Long Island Sound	late June to September	Loosanoff (1942; 1966)
Delaware Bay	late June to September	Hidu (1978)
Chesapeake Bay	mid June to mid October	Beaven (1954) Shaw (1967)
South Carolina	early May to late October	McNulty (1953)
Virginia	mid April to mid October	Chanley and Andrews (1971)
Gulf Coast (Florida to Texas)	late March/early April to late October	Ingle (1951) Hopkins (1954) Hayes and Menzel (1981)

American oyster beds usually have one or two mass spawnings and several smaller spawnings each season. A single bed may have a single mass spawning in one year and two in another year (Shaw 1967), and the number of spawnings does not appear to correspond with latitude. A single female may spawn once or many times (16 have been observed), but most of the eggs are released during the first spawn (Davis and Chanley 1955). The temperatures at which American oysters spawn range from 15° to 20°C in Canada (Kennedy and Battle 1964) to around 25°C in the Gulf of Mexico (Ingle 1951; Hopkins 1954; Hayes and Menzel 1981). Spawning in the laboratory can be induced by thermal stimulation; that is, raising the temperature suddenly by several degrees, or by using a combination of thermal stimulation plus the addition of small quantities of sperm or eggs to the water (Loosanoff and Davis 1963).

Other factors that can affect spawning and gamete vitality are salinity and pH. American oysters in Long Island Sound will develop functional sperm and fertilizable eggs at a salinity as low as 7.5%, but the embryos do not develop normally (Loosanoff 1952). American oysters that are ripened at higher salinities can spawn at 5%. Though American oysters will spawn between pH 6.0 and 10.0, eggs and sperm lose their vitality rapidly when released at these extremes. Gametes at pH 8.0 are viable for 4 to 5 hours. At pH 6.0 or 10.0 they lose their fertilizing ability after 2 to 4 hours (Calabrese and Davis 1969).

Development and Settlement of Larvae

The following larval descriptions and terminology are from Galtsoff (1964) and Carriker and Palmer (1979) (Figure 20). Once eggs are fertilized, they hatch into larvae within 4 to 6 hours. The first larval stage is the free-swimming trochophore, which lasts from 24 to 48 hours. The next is a nonshelled veliger which soon secretes smooth, thin, transparent valves. This first shelled stage is the prodissoconch I, and like that of the blue mussel, is called the straight-hinge stage. The prodissoconch II is formed when more shell is secreted. After further development, the larva is called a pediveliger. At this time the larva is preparing to set. Under adequate conditions the entire larval life is 2 to 3 weeks, with genetic variations in the rate of growth (Newkirk et al. 1977).

American oyster larvae range in length from 60 μm for the prodissoconch I to 350 μm for a set pediveliger Chanley and Andrews (1971). This size range was determined for American oysters from Virginia but should hold for larvae in different areas since, according to Loosanoff et al. (1966), larvae from all points along the east and gulf coasts are the same size at any particular stage of development.

During their 2- to 3-week free-swimming stage, larvae can be widely dispersed from their parental stocks by tidal currents (Loosanoff 1949) and may be found upstream in the tidewaters of rivers and tributaries. Seliger et al. (1982) found that larvae that have developed in surface waters with a "high" saline content can be transported upstream in salinity wedges that penetrate the tributaries. These larvae, which contain highly saline water, sink and are moved upstream with the salinity wedge where they can settle and establish new beds or continue old ones.

At the end of the free-swimming period, the larva settles to the bottom, attaches to some substrate, often called a "clutch", and continues to develop. At this stage, the shell structure begins to look like that of the adult and the young American oyster is called a dissoconch or "spat." Many factors influence settlement (i.e., proper temperature, light, type of substrate, and waterborne pheromones). Hidu (1978) reported that larvae can delay setting to respond to such stimuli. Lutz et al. (1970) observed that a rapid increase in temperature may serve as a stimulus for American oyster setting. Independent experiments by Ritche and Menzel (1969) and Shaw et al. (1970) showed that settlement is encouraged by darkness; the intensity of setting is proportional to the intensity of light, and larval mortality is correlated with the duration of illumination.

Larvae generally set on dead American oyster shells but will also attach to rocks and other surfaces. They do appear to have a preference for some substrates over others. Butler (1954) observed the following order of preference: cement board; American oyster shell; frosted glass; black plexiglass; and white plexiglass. Loosanoff (1958a) demonstrated with laboratory and field experiments that polyethylene was a suitable substrate. Drinnan (1969) observed that scallop shells were an attractive surface.

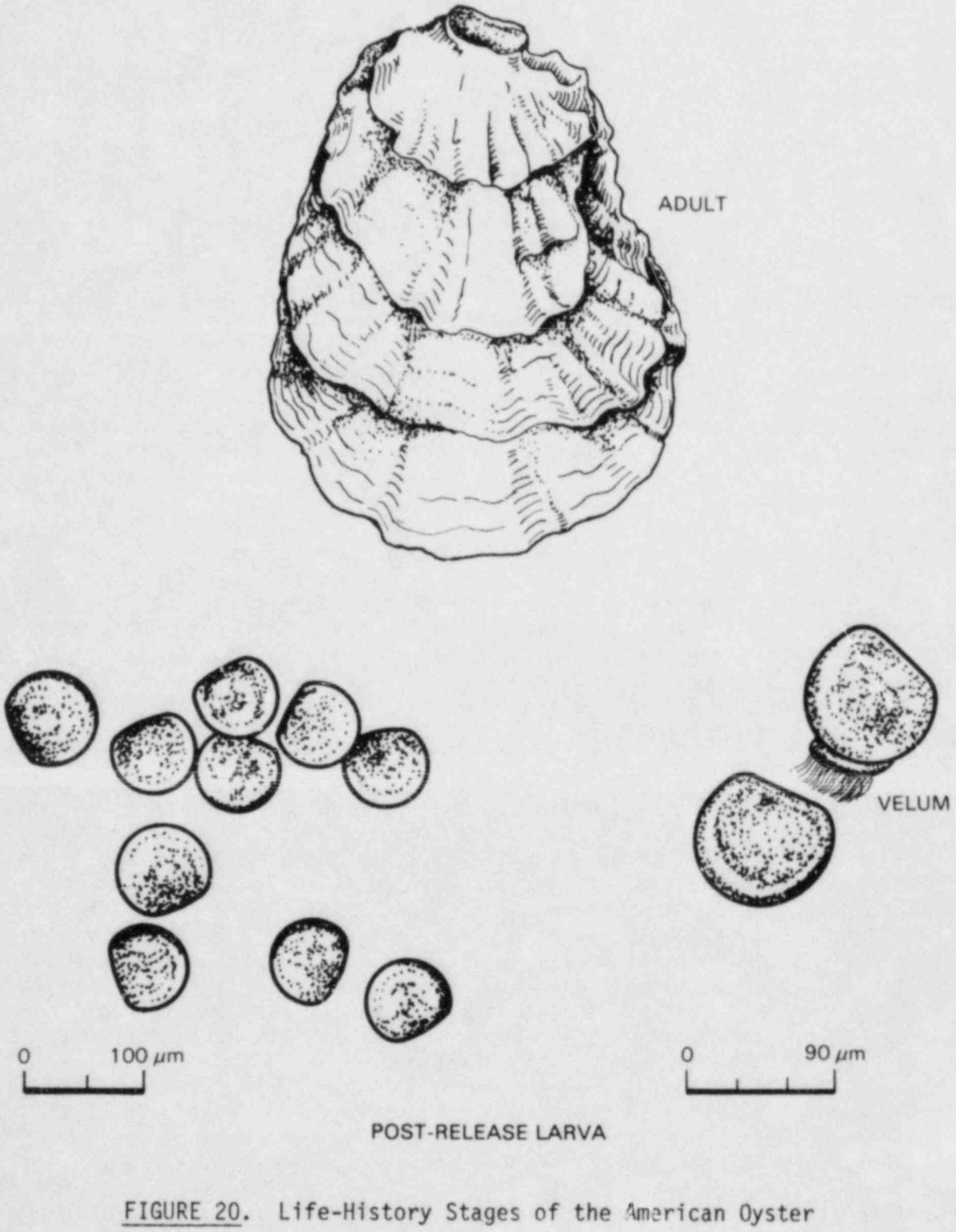

FIGURE 20. Life-History Stages of the American Oyster

Whatever the substrate, it should be clean for a successful set. As little as 3.4 mm (1/75 in.) of sediment on a surface will prevent setting (Butler 1954). Fouling of surfaces by other organisms such as slipper shells (Crepidula) and barnacles causes competition for space and discourages settlement (Ingle 1951; Butler 1954; MacKenzie 1981). American oysters tend to settle in a gregarious manner. A pheromone in the extrapalial fluid of adult American oysters is released into the water to attract larvae to adult beds and encourage setting (Hidu et al. 1969, 1978). The setting factor appears to be a water-soluble protein (Veitch and Hidu 1971).

MacKenzie (1981) reported that about 10% of Long Island Sound spat die soon after setting, probably because of some physiological defect. Newly settled spat may be subject to physical forces as well. Gunter (1979) noticed that small sand-sized particles of dead American oyster shell on shallow American oyster reefs in the Gulf of Mexico will move back and forth with waves and water currents and scour the large shell clutch, killing any newly settled American oysters. This phenomenon was common enough to completely devastate once-productive reefs.

Salinity may influence the depth at which larvae set. Hopkins (1954) found that in the more highly saline waters of the Gulf of Mexico's outer shore, American oysters set intertidally. As salinity progressively decreases in the more inland waters, American oysters set at greater depths.

Factors Affecting Growth

Growth varies considerably with size (age), temperature, quantity and quality of food, seasons of the year, and other environmental conditions. Young American oysters grow faster than old American oysters. In Long Island Sound, a 4- or 5-year-old American oyster will usually be about 9 or 10 cm long, whereas a 40-year-old American oyster (about the maximum age for American oysters) may reach 20 to 25 cm (Loosanoff 1965; MacKenzie 1981). Growth is fastest during the first weeks after setting. In Apalachicola Bay, Florida, Ingle and Dawson (1952) recorded an average growth rate during the first weeks of 0.79 mm/day, but when averaged over 16 weeks, the rate was 0.59 mm/day.

American oysters in northern waters grow more slowly than those in southern waters because of lower temperatures, less food, and shorter seasons. Also, growth naturally ceases during winter. In the northern latitudes, where the water temperature in the winter drops to less than 6° or 7°C, the American oyster enters "hibernation" and ceases to feed, grow, and produce gametes. Not only is less food available during winter, but most American oysters do not feed at temperatures below 5°C (Loosanoff 1958b). The growing season for American oysters in Long Island Sound is approximately from April to November (Loosanoff and Nomejko 1949). In Maine it is only 6 months, June to November (Price et al. 1976). In southern latitudes, where winter temperatures remain relatively high, American oysters may grow all year, and growth may not vary much with season (Ingle and Dawson 1952). As a further example of differences between northern and southern growth rates, American oysters around Prince Edward Island will reach 76 mm in 4 years; in Mississippi they grow to that length in two years (MacKenzie 1975, 1977).

Since temperature can stimulate growth, it is not surprising that American oysters in the heated effluent of an electric generating station often grow faster than those in nearby cooler waters, especially during the cooler seasons of the year (Tinsman and Maurer 1974; Gillmore et al. 1975; Price et al. 1976; Abbe 1980, 1982). American oysters can grow at temperatures from about 6° or 7° to 32°C, but they grow fastest at 25° to 26°C (Galtsoff 1964), and for this reason the power plant thermal discharge can be an attractive means of enhancing growth in young American oysters by commercial American oyster farms during the fall, winter, and spring (Anonymous 1975). Only when the thermal effluent reaches temperatures that are stressful or lethal, usually in summer, is growth retarded (Tinsman and Maurer 1974; Gillmore et al. 1975; Abbe 1982). This can happen in southern latitudes where summer temperatures are naturally high and not much of an increase is required to push the effluent temperature to one that is lethal. It can also happen in cooler waters when the temperature increase (ΔT) by the power plant is high.

Development and growth of eggs (embryos) and larvae are influenced by temperature and salinity. The temperature limits for egg development lie between 18° and 33°C when the salinity is 27°/oo (Davis and Calabrese 1964). A decrease in salinity will narrow these limits. The optimum combination of temperature and salinity for egg development is 25°C and 26°/oo (MacInnes and Calabrese 1979). However, this salinity value was determined from eggs whose parents were kept at about 27°/oo salinity. Davis (1958) showed that the optimum salinity and salinity range in which eggs will develop into straight-hinge larvae depends on the salinity at which the parent American oysters develop their gonads. American oysters that are conditioned at 26 to 27°/oo have an optimum salinity of 22.5°/oo for egg development. The optimum salinity for egg development of American oysters from 9°/oo is about 10 to 15°/oo, and the survival range is from 7.5 to 22.5°/oo.

Davis and Calabrese (1964) noted that the survival of larvae is 70% or better at temperatures from 27.5° to 32.5°C in the salinity range of 10 to 27°/oo, but the best growth occurs from 15 to 27°/oo. Below 20°C, larval growth is slow, but it increases dramatically above 20°C. The lowest temperature at which any growth occurs is 6° to 7°C (MacKenzie 1981). Growth is also slowed at 35.0°C. Hidu et al. (1974), using American oysters from Chesapeake Bay that were conditioned at temperatures ranging from 20° to 25°C and salinities between 10 and 15°/oo, measured the average lethal dose for 50% of the test population (LD-50) for all larval stages at 42°C with a 10-second exposure, at 38°C with a 10-minute exposure, and at 33°C with a 2-hour exposure. Longer exposure times did not appreciably decrease the LD-50 temperature. At low temperatures the LD-50 was about 17°C after a 2-hour exposure. They also found that developing eggs were much less tolerant to high temperatures than were later larval stages.

Other environmental factors that can affect eggs and larvae include pH, metal concentrations, chlorine, and ozone. The optimal pH range for American oyster egg development and larval growth is 6.25 to 8.75, and survival drops rapidly outside these values (Calabrese and Davis 1966). Several divalent metals are toxic to American oyster embryos Calabrese et al. (1973). Of eight metals tested, mercury was the most toxic. The 48-hour lethal concentration for 50% of the test population (LC-50) was 5.6 parts per billion (ppb) for mercury, 5.8 ppb for silver, 103 ppb for copper, 310 ppb for zinc, 1180 ppb for nickel, 2450 ppb for lead, and 3800 ppb for cadmium. Metal toxicity tests with four metals indicated that larvae are less sensitive than embryos. The 12-day LC-50 for mercury, silver, copper, and nickel were 12.0, 25.0, 32.8, and 1200 ppb, respectively. Growth was highly reduced at the LC-50 concentrations. The embryos and larvae were tested at approximately 25°C at a salinity of 25°/₀₀. The metals may be more toxic at higher or lower temperatures or at lower salinities (MacInnes and Calabrese 1978, 1979).

The relative toxicity of chlorine produced oxidant (CPO) to developing American oysters depends on the age of the American oysters. Set juveniles are more resistant than pediveligers, and pediveligers are more resistant than straight-hinge larvae (Roberts et al. 1975; Roberts and Gleeson 1978; Roosenburg et al. 1980). The LC-50 values for larvae are 0.3 ppm at 48 hours, 0.08 ppm at 72 hours, and 0.06 ppm at 96 hours (Roosenburg et al. 1980). Mortality is greater with continuous chlorination than with intermittent additions (Roberts et al. 1975), and increases as temperature increases. Also, chloramines are more toxic than free chlorine (Capuzzo 1979).

Ozone appears to be slightly less toxic to American oyster larvae than chlorine, and again, older larvae are more tolerant than younger larvae. The LC-50 values for ozone produced oxidants (OPO) for straight-hinge larvae are 0.36 ppm at 48 hours, 0.19 ppm at 72 hours, and 0.12 ppm at 96 hours (Richardson et al. 1982). Less than 0.18 ppm can damage eggs in 2 hours; fertilization is reduced, development is retarded, and OPO causes developmental abnormalities (MacLean et al. 1973).

Laboratory experiments by Chanley (1957) demonstrated that set juveniles from Long Island Sound fail to grow at salinities below 5°/₀₀, grow slowly at salinities below 12°/₀₀, and grow normally in salinities ranging from 12 to 27°/₀₀. American oysters living in areas with fast currents may grow quickly because the current brings in fresh food; American oysters growing in areas where currents are slower will grow slowly, if at all (Shaw and Merill 1966). American oysters living in deep water (>30 m) grow more slowly than American oysters in shallow water (Merrill and Boss 1966). Low levels of chlorine can reduce growth in juveniles (Roberts et al. 1975). And finally, American oysters that were genetically fast growers as larvae will continue fast growth rates as juveniles (Newkirk et al. 1977).

DESIGN CHARACTERISTICS OF RAW-WATER SYSTEMS

Engineering characteristics common to raw-water systems may allow or even exacerbate bivalve fouling. This section describes the various types of raw-water systems in use, their importance to safe plant operation, and identifies systems and components that are most likely to be fouled.

Raw-water systems typically provide cooling water to reactor support systems, turbine-generator support systems, and to the main condensers of the circulating-water system. Although there are many plant-to-plant differences in raw-water systems, these three systems are common to most commercial boiling water reactors (BWR) and pressurized water reactors (PWR). Only those raw-water 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 (U.S. AEC 1974).

The raw-water source may be a river, lake, estuary, or ocean. Pumps used to draw cooling water into a plant are usually housed in and protected by an intake structure. Intake structure design and maintenance can affect fouling within a raw-water system. Raw water is also a common source of water for the fire protection system in freshwater-cooled plants. Saltwater-cooled plants usually draw fire protection water from ground wells.

Although bivalve fouling has occurred in both nuclear and non-nuclear-related systems, the emphasis of this report is on systems and components that are nuclear safety-related. Fouling data were, however, compiled for all raw-water systems to increase the data base from which to identify correlations between biological fouling and engineering characteristics that influence fouling.

Components in Safety Class 3 are designed to Seismic Category I requirements. Seismic Category I requires that plant structures, systems, and components important to reactor safety be designed to withstand the effects of a safe shutdown earthquake and remain functional to ensure: 1) the integrity of the reactor coolant pressure boundary, 2) the capability to shut down the reactor and maintain it in a safe condition, or 3) the capability to prevent or mitigate the consequences of accidents which could result in potential offsite exposures comparable to the guideline exposures of 10 CFR 100.

Nuclear, safety-related, raw-water cooling loops in commercial BWRs and PWRs 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 raw-water systems of typical freshwater-cooled PWR and BWR plants where Asiatic clam fouling has occurred.

A later discussion (see p. 95) will address the major differences between the designs of these raw-water systems and designs used at saltwater-cooled plants.

BWRs and PWRs have similar main circulating-water systems and fire protection systems and these systems are therefore treated alike in the following discussion. Separate descriptions are given for BWR and PWR reactor-support systems and turbine-generator support systems. Due to the many plant-to-plant differences in raw-water systems, the systems described here may differ somewhat from those of specific freshwater plants. These descriptions are given to provide the reader with a general knowledge of the design and function of raw-water systems and are not intended to represent any one BWR or PWR plant.

REACTOR SUPPORT SYSTEMS OF PRESSURIZED WATER REACTORS

Raw-water systems that provide cooling to reactor support systems in a PWR are often designated as the service-water system (sometimes called the nuclear service-water system or the essential service-water system). Components cooled by the service-water system are located in the reactor building (containment building) and the auxiliary building. Service-water system components are generally rated as nuclear Safety Class 3.

Heat exchangers in freshwater-cooled PWR plants are often cooled directly by service water (Table 2, Figure 21). Figure 21 was developed from piping and instrument diagrams and has been greatly simplified to show the parallel (redundant) flow paths (trains A & B), inlet piping diameters, and redundant heat exchangers common to PWR service-water systems. Inlet valves to heat exchangers are included to show which areas are normally open (NO), normally closed (NC), or used on demand (OD). Valves that are used on demand correspond to heat exchangers used intermittently. Room coolers, for example, are used on demand to limit the temperature in areas where critical equipment is located. When the air temperature reaches a prescribed limit, the valve opens and allows service-water to flow through the room cooler.

During normal operation, only a fraction of the total number of heat exchangers in Train A of Figure 21 are used continuously. The rest are either used intermittently during normal operation or are 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 3. Five heat exchangers are used continuously, and six are used intermittently (Table 3). Considering both trains A and B, only 11 out of 55 (20%) of the heat exchangers in this typical service-water system are used during normal operation. The large percentage of heat exchangers not used during normal operation (80%) has been an important factor contributing to fouling by the Asiatic clam.

TABLE 2. Nuclear Safety-Related Components Typically Supplied with Service Water

- 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
    - the cable spreading room
    - the electric auxiliary room
- Bearing coolers to:
    - RHR pumps
    - containment spray pumps
    - high 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

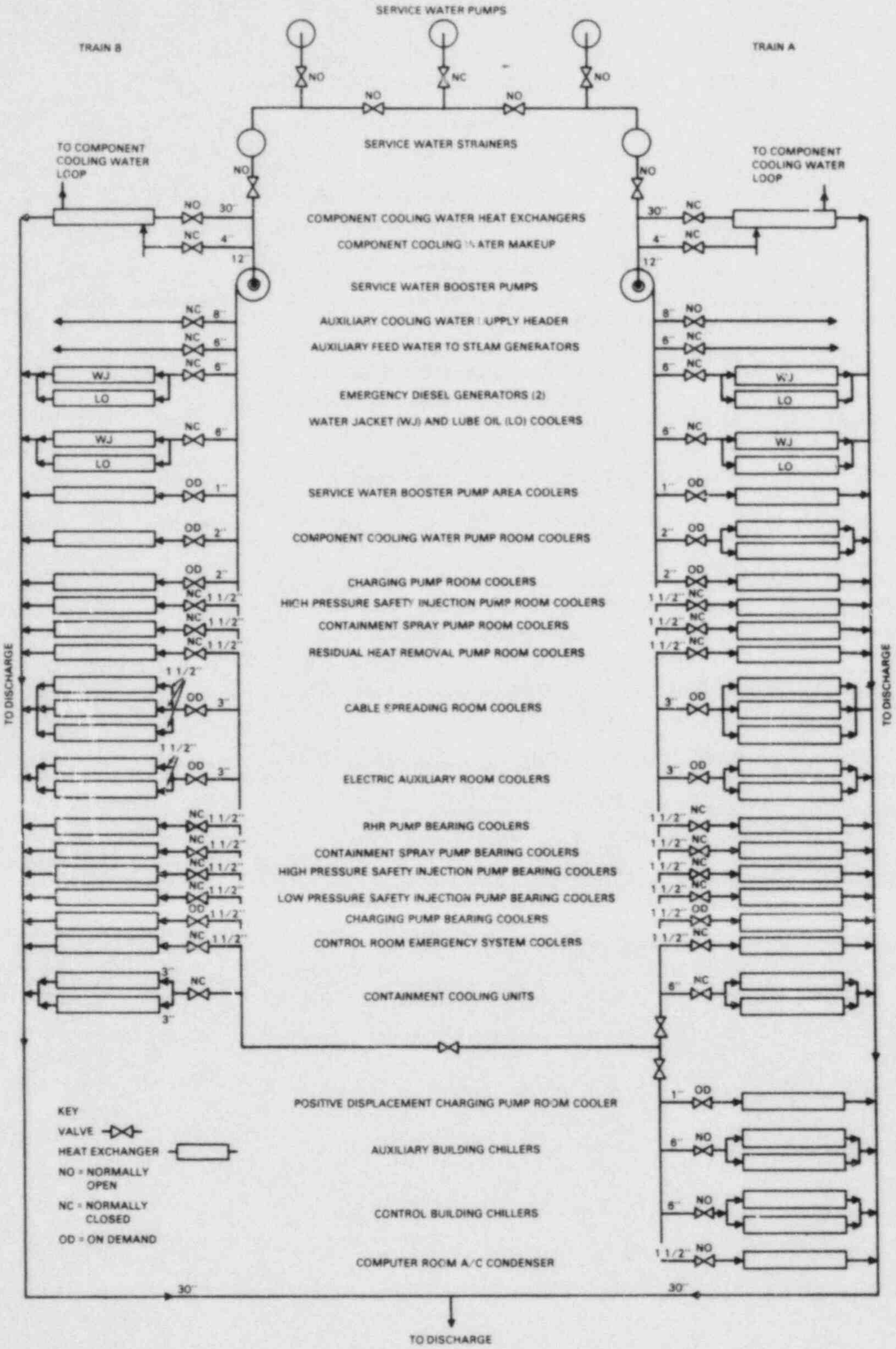

FIGURE 21. Typical PWR Service-Water Flow Design

TABLE 3. Heat Exchangers Used During Normal Operation

Continuous Use

Component cooling water heat exchangers (A & 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
Electric auxiliary room cooler
Charging pump room cooler
Charging pump bearing cooler

The component-cooling water heat exchangers demand the largest portion of the total service-water flow. Design flow for the service water pumps in Figure 21 is 1260 ℓps (20,000 gpm) per pump. Two pumps are in operation during normal conditions, giving a total flow of 2520 ℓps (40,000 gpm). Approximately 2140 ℓps (34,000 gpm), i.e., 85% of the flow, is required by the two component cooling-water heat exchangers. The component-cooling water loop cools various components that circulate potentially radioactive coolant and serves as an intermediate loop between portions of the reactor coolant system and the service-water system. This double barrier reduces the probability that potentially radioactive coolant will leak into the service-water system. Also, the component-cooling loop is maintained at a lower pressure than the service-water system so that any leakage is directed to the loop and not to the service-water system for subsequent release from the plant. The systems and components cooled by the component-cooling water system are listed in Table 4. These components are cooled indirectly by service-water through the closed-loop component-cooling water system using the component-cooling water heat exchangers. Table 4 lists five heat exchangers that are included in the service-water system at some plants and are cooled directly by raw water. This is due to the variability allowed in cooling systems design. A simplified flow diagram showing the typical two-loop design and the redundant heat exchangers in the component cooling water system is shown in Figure 22. Most valves have been omitted to improve the clarity of the diagram. Valves are shown for the residual heat removal (RHR) heat exchangers (sometimes called shutdown-cooling or decay-heat removal heat exchangers) because they are used only during shutdown of the reactor or during extended outages to remove decay heat from the reactor core.

TURBINE-GENERATOR SUPPORT SYSTEMS OF PRESSURIZED WATER REACTORS

Raw-water systems that cool turbine-generator support systems in PWR plants are often designated as the auxiliary cooling-water system (sometimes called

TABLE 4. PWR Systems and Components Cooled by the Component-Cooling Water System

Residual Heat Removal System

- RHR heat exchangers
- RHR pump bearing coolers*

Chemical Volume and Control System

- letdown heat exchangers
- excess letdown heat exchanger
- boric acid vent condenser
- boric acid evaporator condenser
- boric acid evaporator distillate cooler
- charging pump bearing coolers*

Reactor Coolant Pumps

- cooling coils
- lube oil coolers
- seal water cooler

Sampling System

- reactor coolant sample cooler
- safety injection sample cooler
- pressurizer vapor space sample cooler
- pressurizer surge sample cooler

Waste Disposal System

- waste gas compressors and aftercoolers
- rad waste evaporator condensers
- rad waste evaporator vent condensers
- rad waste evaporator distillate cooler

Spent Fuel Pool Heat Exchangers

High Pressure Safety Injection Pump Bearing Coolers*

Low Pressure Safety Injection Pump Bearing Coolers*

Containment Spray Pump Bearing Coolers*

---

*Components sometimes cooled directly by service water (also listed in Table 2).

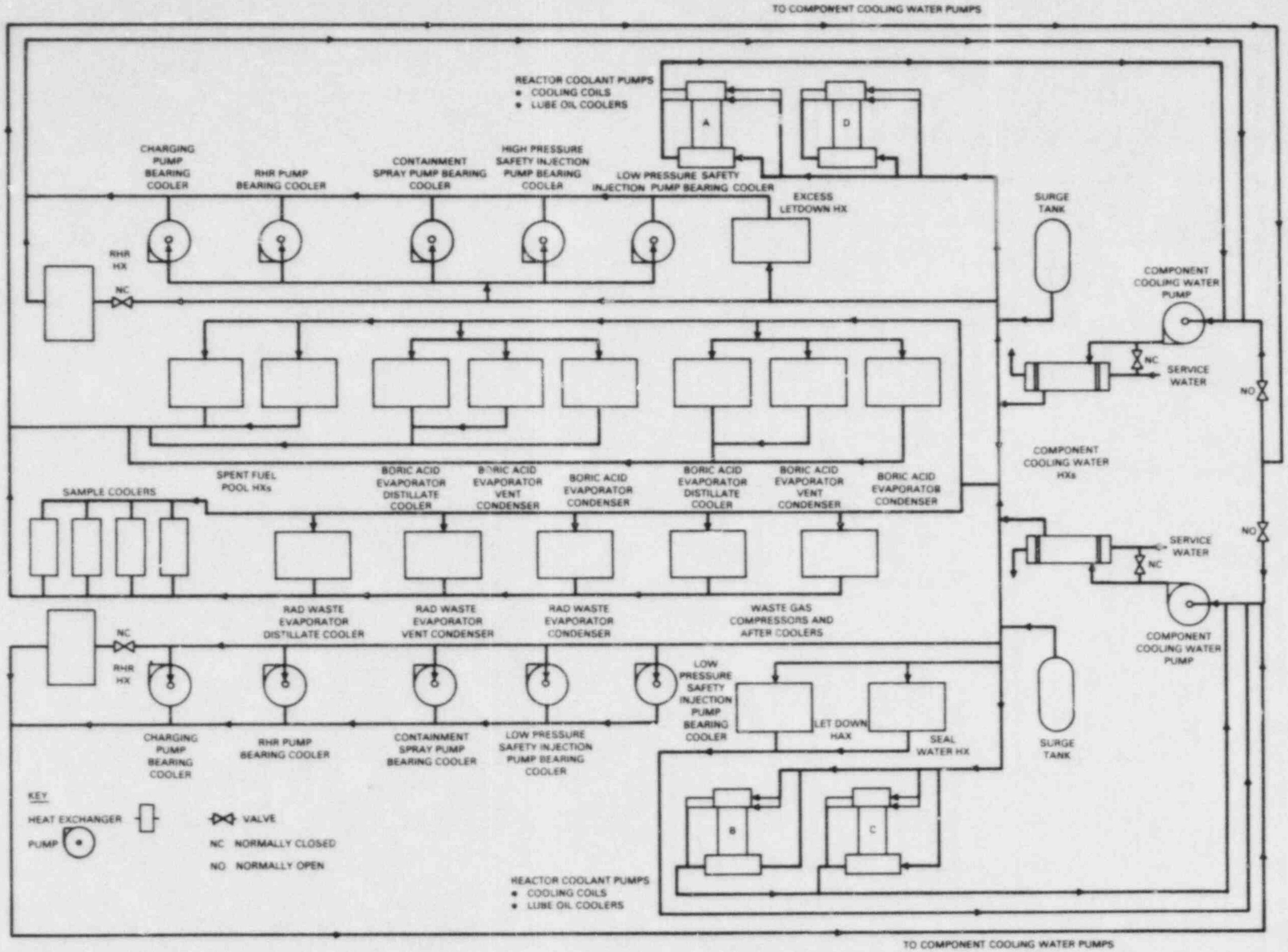

FIGURE 22. Flow Diagram of a Typical PWR Component-Cooling Water System

the turbine-building cooling-water system, the raw cooling-water system, or the nonessential service-water system). Components cooled by the auxiliary cooling-water system are located in the turbine-generator building. Raw water may be provided by auxiliary cooling-water pumps located in the intake structure, or from a branch header off of the service-water system. Table 5 lists heat exchangers cooled by the auxiliary cooling-water system, and Figure 23 shows a simplified flow diagram. The auxiliary cooling-water system is not required for safe shutdown of the reactor and, therefore, is not safety-related.

RAW-WATER SYSTEMS OF BOILING WATER REACTORS

The raw-water systems serving the reactor and turbine-generator support systems in typical freshwater BWR plants can be divided into three functional groups: the raw cooling water (RCW) system; the residual heat removal, service-water (RHRSW) system; and 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 shutdown conditions, and the EECW system is used during emergency conditions. Components cooled by raw water are located in the reactor building, auxiliary building, and turbine building. Raw-water system components serving reactor-related systems are typically rated Safety Class 3. Those components serving turbine-generator loads are generally classified as power-conversion systems and are not nuclear safety-related.

TABLE 5. Typical Components Served by a PWR Auxiliary Cooling-Water System

Turbine-generator lube oil coolers
Turbine-generator electro-hydraulic fluid coolers
Generator stator coolers
Generator hydrogen coolers
Generator exciter coolers
Generator hydrogen seal oil coolers
Feedwater pump turbine lube oil coolers
Main turbine steam packing exhauster condenser
Condensate pump motor lube oil coolers
Heater drain pump motor lube oil cooler
Non-nuclear sample coolers

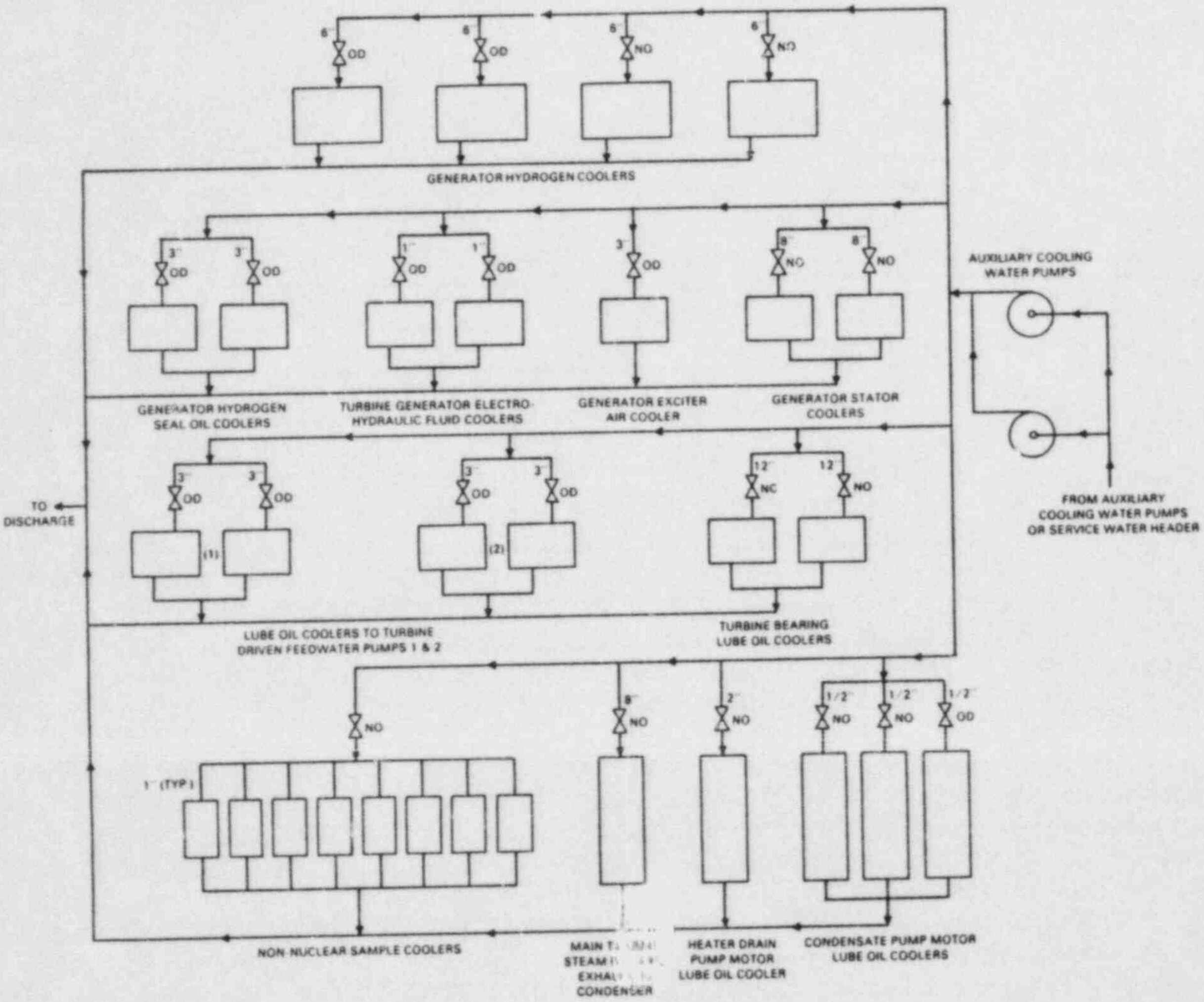

FIGURE 23. Flow Design of an Auxiliary Cooling-Water System in a PWR

Heat exchangers cooled by raw water in several freshwater BWR plants are listed in Table 6. Components listed in Table 6 include those in the RCW, RHRSW, and EECW systems. The specific components served by each of these systems are discussed later in this section. Figure 24 presents a simplified flow diagram showing the heat exchangers listed in Table 6 and shows the parallel flow paths, inlet piping diameters, and redundant components common to BWR raw-water systems. Figure 25 also indicates which valves are normally open, normally closed, or used on demand.

Heat exchangers using raw water either operate continuously or intermittently during normal operation, or only during shutdown or emergency conditions. Again, parallel cooling trains provide a 100%-capacity backup system. Table 7 shows the heat exchangers in the RCW system; nine are used continuously and three are used intermittently during normal operation. Thus, of approximately 50 heat exchangers served by raw-water at a typical freshwater BWR plant, about 20% are used during normal operation.

Raw-Cooling Water Systems of Boiling Water Reactors

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 25. RCW pumps typically take suction at the plant intake structure, although at some plants the pumps take suction from the circulating water header upstream of the circulating water pumps. The RCW system is typically not safety-related nor is it essential to safe shutdown of the plant. A Seismic Category I backup water supply is provided by the EECW system for the safety-related components cooled by the RCW system.

The RBCCW loop is an intermediate cooling loop between portions of the reactor coolant system and the RCW system. The RBCCW loop cools components that circulate potentially contaminated liquids and provides an intermediate barrier to reduce the potential for release of radioactive material to the RCW system. Pressure in the the RCW system is maintained higher than that in the RBCCW system to ensure that any leakage of contaminated liquid is directed into the closed system. Components and systems that are cooled by the RBCCW loop are listed in Table 8. A simplified flow diagram showing the parallel loop design and redundant heat exchangers is shown in Figure 26. The RBCCW system is generally classified as a power conversion system and is not safety-related even though it provides cooling to some safety-related equipment during normal operations. An alternate safety-related cooling water supply is provided to the RBCCW heat exchangers by the EECW system for use during emergency conditions.

The RCW system also provides cooling water to the turbine building closed-cooling water (TBCCW) heat exchangers and other equipment associated with turbines. The TBCCW system is an intermediate cooling loop designed to remove heat from heat exchangers in the turbine building and the radwaste building. Raw cooling water is typically provided from a branch

TABLE 6. Heat Exchangers Cooled by Raw Water at Various BWR Plants

Residual heat removal (RHR) heat exchangers *
Reactor building closed cooling water (RBCCW) heat exchangers
RBCCW system pump and room coolers
RHR pump seal and bearing coolers *
RHR pump room coolers *
Control rod drive pump motor, oil, and bearing coolers
Control air compressors
Station service air compressors
Core spray pump bearing coolers *
Core spray room coolers *
Diesel generator water jacket and lube oil coolers *
Containment cooling units (drywell cooling units) *
Reactor water cleanup pump coolers
Control room air conditioning chilled water condensers *
Reactor building standby ventilation system condensers
Relay room, emergency switchgear, and computer room A/C system *
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

---

*Denotes nuclear safety related component.

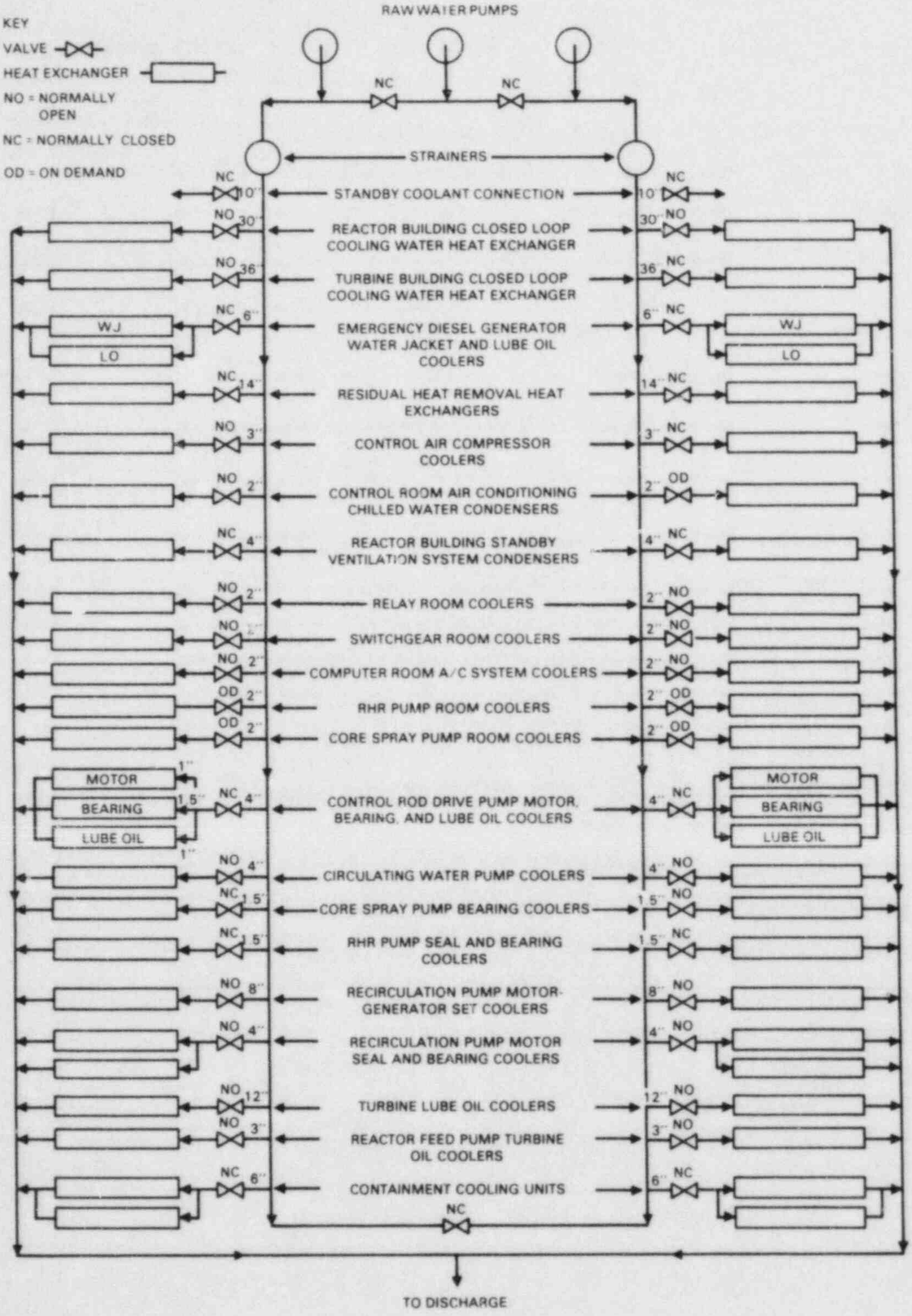

FIGURE 24. Flow Diagram Showing Typical BWR Components Cooled by Raw Water

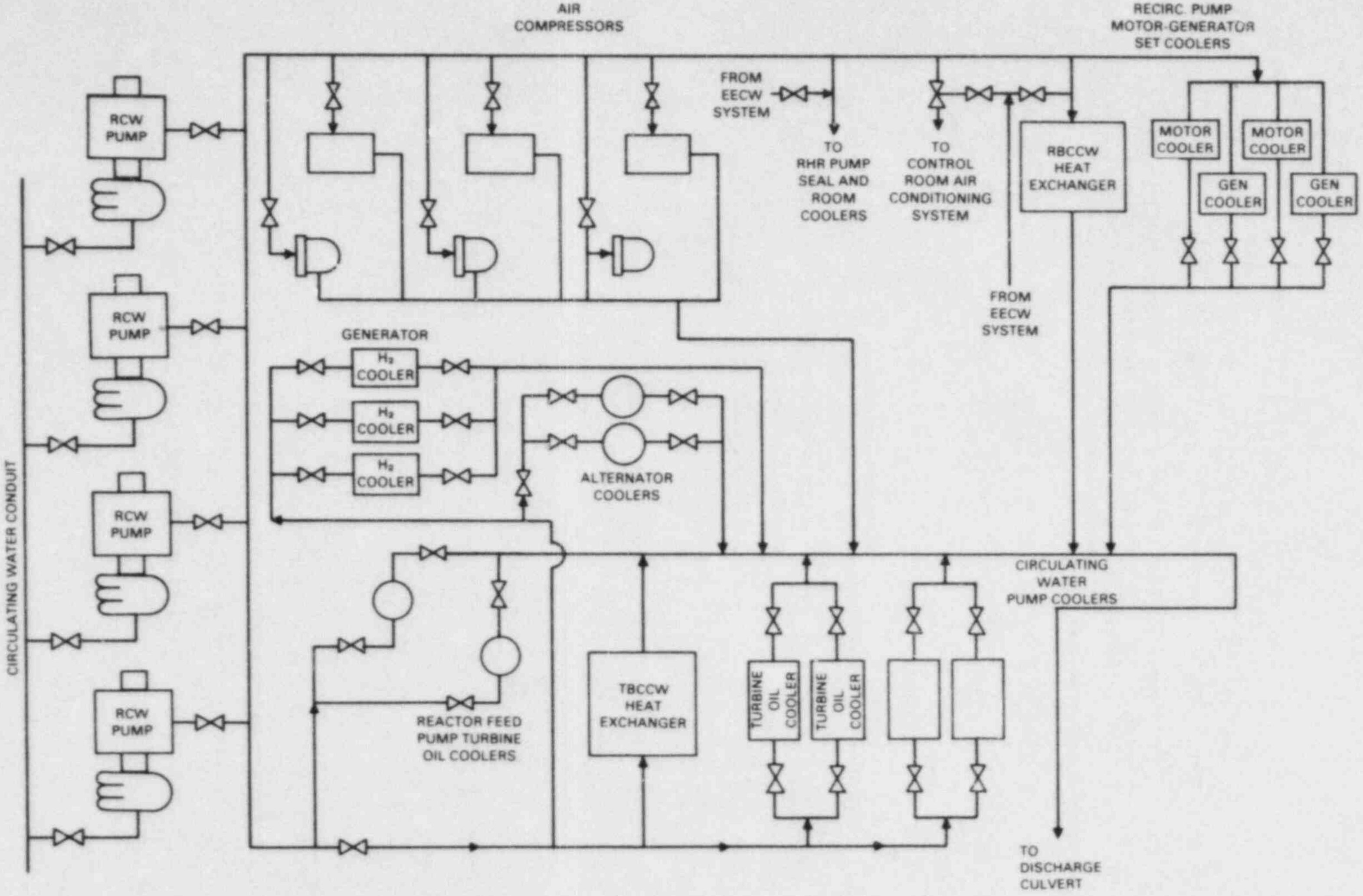

FIGURE 25. Flow Diagram of a Typical BWR Raw-Cooling Water System

TABLE 7. BWR Heat Exchangers Used During Normal Operation

Continuous Use

Reactor building closed-cooling water heat exchangers
Turbine lube oil coolers
Service and control air compressors and after-coolers
Control room air conditioning chilled water condensers
Turbine building closed loop cooling water heat exchangers
Reactor feed pump turbine oil coolers
Recirculation pump motor-generator set coolers
Relay room, emergency switchgear room, and computer room A/C system coolers

Intermittent Use

RBCCW pump and room coolers
Motor control center and motor-generator room coolers in reactor building

TABLE 8. BWR Systems and Components Cooled by the Reactor Building Closed Cooling-Water System

Recirculation pump motor coolers
Recirculation pump seal coolers
Drywell atmosphere coolers
Control rod drive supply pump coolers
Drywell and reactor building sump coolers
Cleanup recirculation pump coolers
Spent fuel storage pool heat exchangers
Waste concentrator condenser (at some plants)
Drywell control air system compressor and after coolers
Reactor water sample coolers

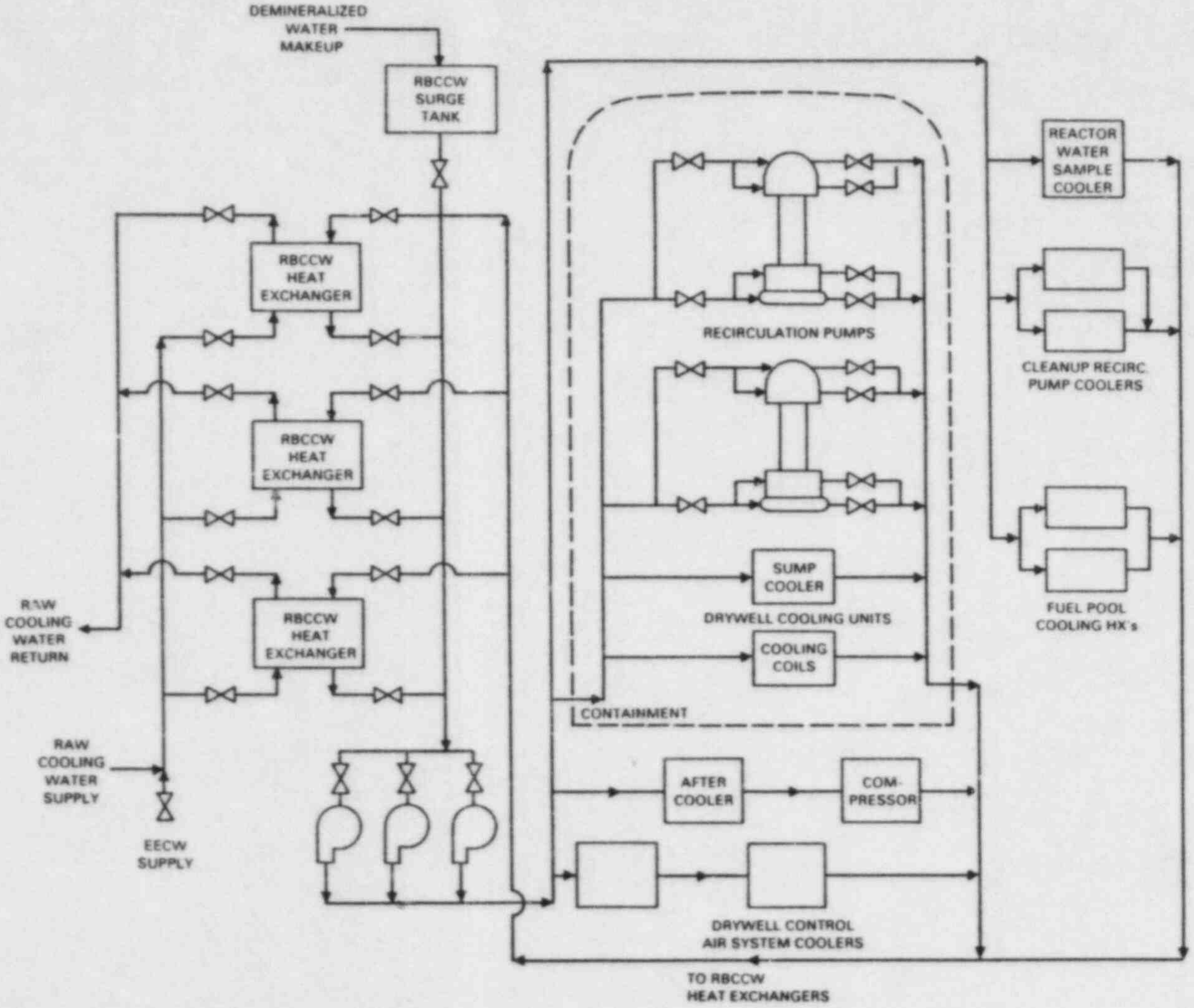

FIGURE 26. Flow Diagram Showing the Parallel Loop Design and Redundant Heat Exchangers of the Reactor Building Closed Cooling-Water System of BWRs

header off of the RCW system but can also be provided by auxiliary pumps located in the intake structure. Again, RCW system pressure is maintained higher than TBCCW pressure to prevent the release of contaminated coolant to the environment. Heat exchangers cooled by the TBCCW are listed in Table 9, and a simplified flow diagram of the system is shown in Figure 27. This system is not required for safe shutdown of the plant and therefore is not safety-related.

Residual Heat Removal Service-Water System of Boiling Water Reactors

The residual heat removal service-water (RHRSW) system provides water to remove heat from the RHR system. The RHRSW system includes pumps, piping, valves, and instrumentation necessary to provide raw cooling water to the RHR heat exchangers. Typically, the system also supplies raw water to the EECW system. A simplified flow diagram of the RHRSW and EECW systems is shown in Figure 28. The RHRSW and RHR systems are safety-related and thus are designed to Seismic Category I standards. Neither system is operated during normal power operations and are therefore considered to be intermittently used systems.

TABLE 9. BWR Systems and Components Cooled by the Turbine Building Closed-Loop Cooling-Water System

Reactor feed pump turbine oil coolers
Generator hydrogen coolers
Generator leads coolers
Main turbine lube oil coolers
Condensate pump motor bearing coolers
Condensate booster pump lube oil coolers
Offgas vent coolers
Alternator cooler
Condenser air removal pump cooler
Waste evaporator overheads condenser
Waste evaporator distillate cooler

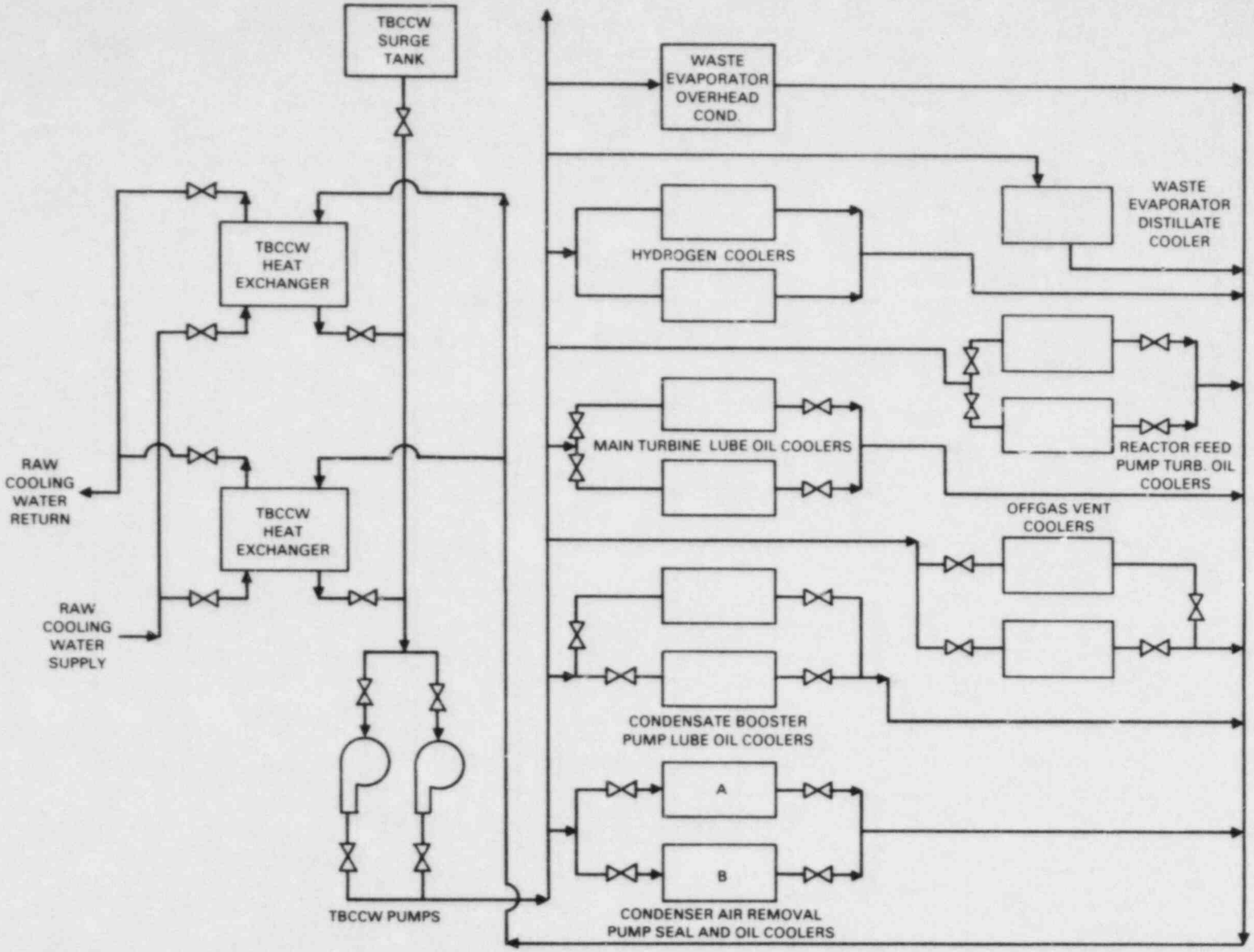

FIGURE 27. Flow Diagram of a Typical BWR Turbine Building Closed-Cooling Water System

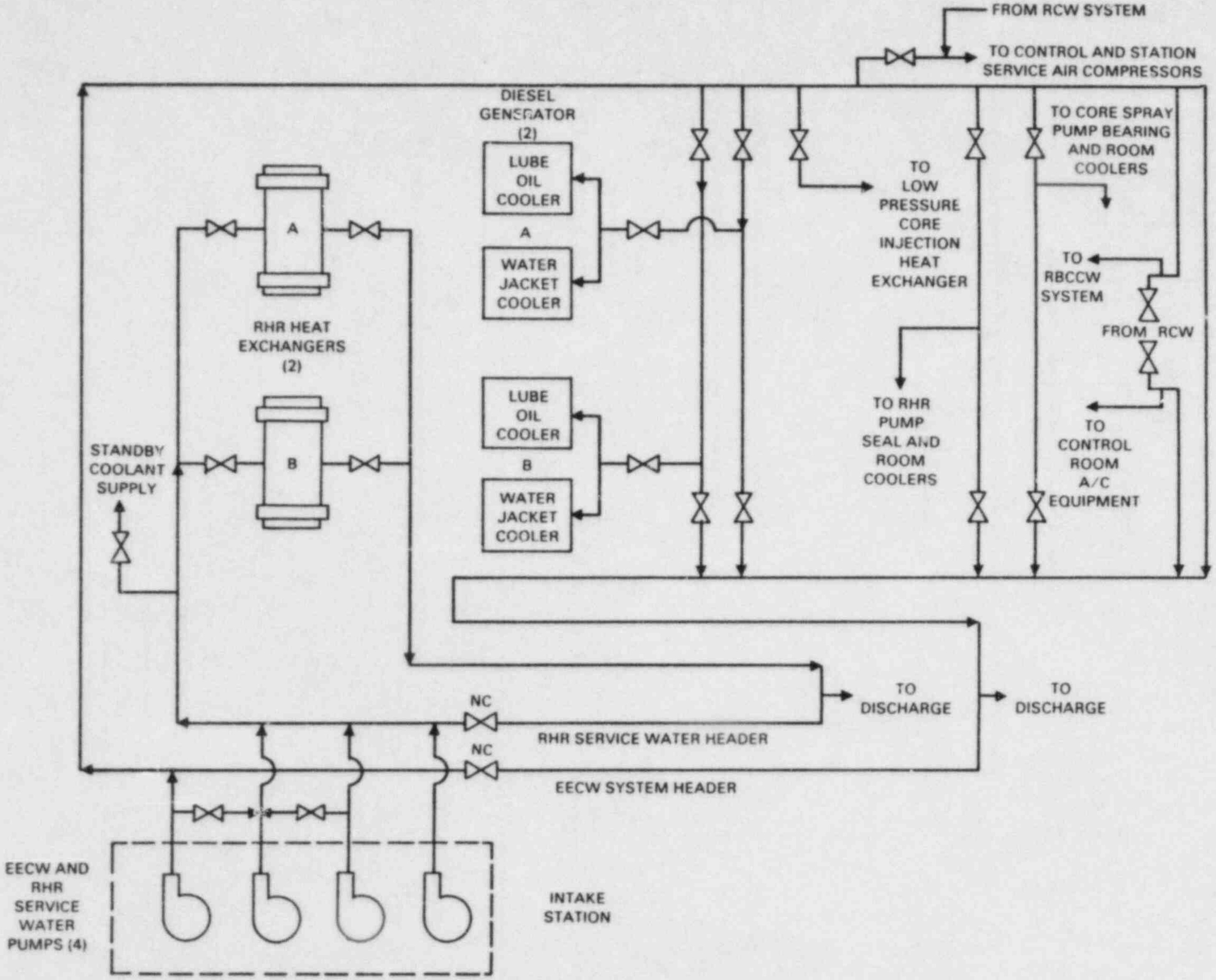

FIGURE 28. Flow Diagram of the Residual Heat Removal Service-Water System and Emergency Equipment Cooling-Water System

The RHRSW system operates in several different modes under different conditions. Under shutdown conditions, the system supplies raw water to the RHR heat exchangers, which are used to 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 for reactor vessel and containment flooding after a potential loss-of-coolant accident. In addition, raw cooling water flowing through the RHR heat exchangers 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 capability.

Emergency Equipment Cooling-Water System of Boiling Water Reactors

The emergency equipment cooling-water (EECW) system supplies cooling water required for operation of safety-related components in the core spray, RHR, and diesel generator systems. Typically, the EECW system can also 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. Pumps assigned to EECW service are generally located in the intake pumping station. The EECW system is a safety system and is designed to Seismic Category I specifications. Parallel and redundant pump trains are assigned to the EECW system. Generally, the RHRSW and EECW systems are closely associated with each other (e.g., both system may share common pumps) and may serve as backups for each other.

The EECW system provides long-term, post-accident cooling of emergency components. A simplified flow diagram of the EECW system was shown previously (see Figure 28). The RHR system components cooled by the EECW system (Table 10) are normally supplied by the RCW system. Therefore,normal shutdown of the reactor can be accomplished without the use of EECW. Under accident conditions, RCW will be replaced by EECW, and the RCW system becomes the backup supply.

VARIATIONS IN DESIGN OF RAW-WATER SYSTEMS AT SALTWATER-COOLED PLANTS

The raw-water systems described previously for freshwater PWR and BWR plants are typical of what may be called open-cycle cooling systems. That is, raw water is used directly to cool most of the heat exchangers serving the reactor and turbine-generator systems. This type of cooling system is common in freshwater plants where a large volume of relatively clean, noncorrosive raw water is available from a river or lake. Open-cycle cooling systems generally have many small heat exchangers that are cooled directly by raw water.

Saltwater-cooled plants are designed to minimize the number of components that interface directly with saltwater. This is because of the corrosive nature of saltwater and the known threat of biofouling in marine environments. Closed-cycle cooling loops are used to cool the majority of heat exchangers serving the reactor and turbine-generator systems. The

TABLE 10. BWR Systems and Components Cooled by the Emergency Equipment Cooling-Water System

Core spray room coolers

Core spray pump bearing coolers

RHR room coolers

RHR pump seal coolers

Diesel generator water jacket and lube oil coolers

Low pressure core injection system heat exchangers

Control room A/C chilled water condensers (backup supply)

Reactor building standby ventilation system condensers (backup supply)

Reactor building closed cooling water heat exchangers (backup supply)

Control and station service air compressors (backup supply)

closed-cycle loops are, in turn, cooled by saltwater. In contrast to open-cycle systems which typically have 50 or more small heat exchangers that are cooled directly by raw water (Figures 21 and 24), closed-cycle systems typically have a smaller number of large heat exchangers (about 12 to 15) that are cooled directly by raw water. The reduced number of heat exchangers confines corrosion and marine biofouling to fewer components. The flow diagram in Figure 29 is typical of both PWR and BWR raw-water systems in saltwater plants. Three 50%-capacity heat exchangers (the third is a backup) are provided for the reactor building closed-cooling water (RBCCW) system, the turbine-building closed-cooling water (TBCCW) system, and each of the two emergency diesel generators.

In the previous description of a freshwater BWR system, the RBCCW and TBCCW systems cooled only those heat exchangers that circulated potentially radioactive water. In saltwater systems (Figure 29), the RBCCW and TBCCW heat exchangers cool virtually all heat exchangers that serve the reactor and turbine-generator systems, respectively. In most BWR plants, RHR heat exchangers are cooled directly by saltwater. When the RHR heat exchangers are not in use, they are purged and filled with potable or demineralized water.

Closed-cycle raw-water systems are also used in some of the latest freshwater plants. Two examples of this are the Oconee and Palo Verde plants. In a freshwater environment, the major advantage of a closed-cycle system is the reduced number of heat exchangers in which Asiatic clams and silt can accumulate. Additionally, the heat exchangers are substantially larger than most heat exchangers in open-cycle systems and the flow velocity through them is much higher. Both factors make it harder for Asiatic clams and silt to settle in the system.

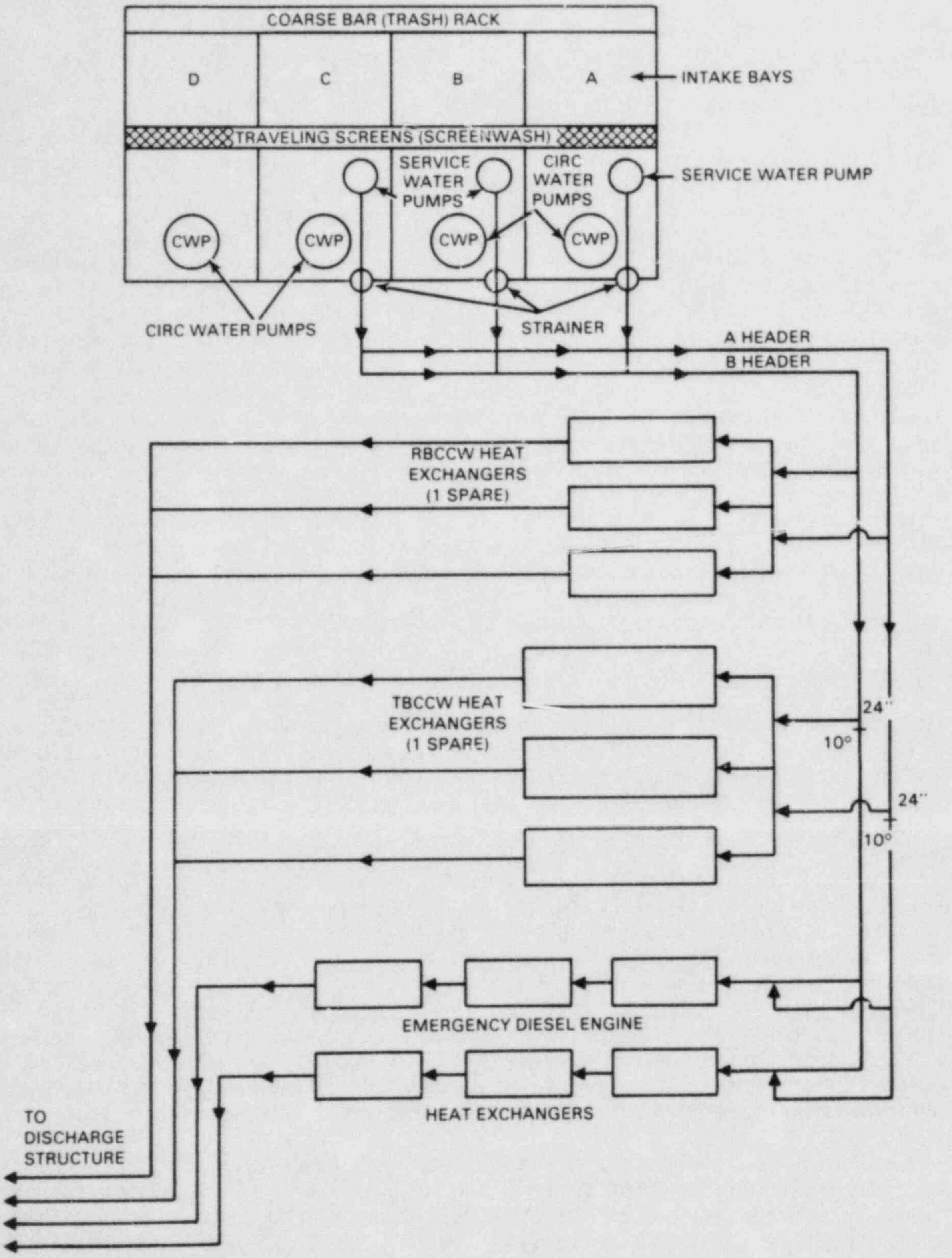

FIGURE 29. Flow Diagram of a Typical Closed-Cycle System at a Saltwater-Cooled Plant

MAIN CIRCULATING-WATER SYSTEM OF PWRs AND BWRs

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 non-nuclear Safety Class 4.

Circulating-water systems are designed for one of the three types of operation: once-through cooling, closed-cycle cooling, or a combination of both ("helper" mode). Once-through cooling is common in saltwater plants, whereas closed-cycle cooling is more common in freshwater plants. In once-through circulating-water systems, water is pumped from the raw-water source, passed through the condensers, and returned to the water body. Closed-cycle circulating-water systems use cooling towers (natural draft or mechanical forced draft) or large cooling ponds to cool water 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 structure or from the service-water discharge. Some plants have the capability to operate in either the once-through, closed-cycle, or "helper" mode. The Browns Ferry plants, for example, can operate in any of these three modes. Helper mode provides a combination of cooling from the cooling towers and the raw-water source. Figure 30 shows a simplified flow diagram of a circulating-water system capable of these three modes of operation.

FIRE PROTECTION SYSTEMS OF PWRs AND BWRs

The high pressure fire protection system (HPFP) is designed to provide a reliable source of water for use in the event of fire. Fire protection water is typically provided by the raw-water system in freshwater plants and by ground wells in saltwater-cooled plants. Macroinvertebrate fouling in fire protection systems has been restricted to Asiatic clam fouling in freshwater plants.

Water is typically supplied to the high pressure fire protection system by one of two motor-driven fire pumps (one is a backup) (Figure 31). These pumps are located in the intake structure and normally supply from 126 to 190 ℓps (2000 to 3000 gpm) each. The distribution system includes a pipe loop that encircles the entire plant and directly feeds the automatic spray systems in the yard. Branch loops and interconnecting piping provide water to automatic spray and fog systems inside the plant as well as hose connections and fire hose racks throughout all plant buildings. Major areas provided with fire protection water systems are listed in Table 11.

Pressure is maintained in the HPFP system by jockey pumps fed by the service water or raw-cooling water system, and in some cases by raw-water storage tanks located on top of the reactor building. Jockey pumps can also provide a reduced flow volume for fire fighting purposes. The high pressure fire pumps are triggered by a drop in system pressure or by automatic fire system indicators. They can also be started manually for system flow tests.

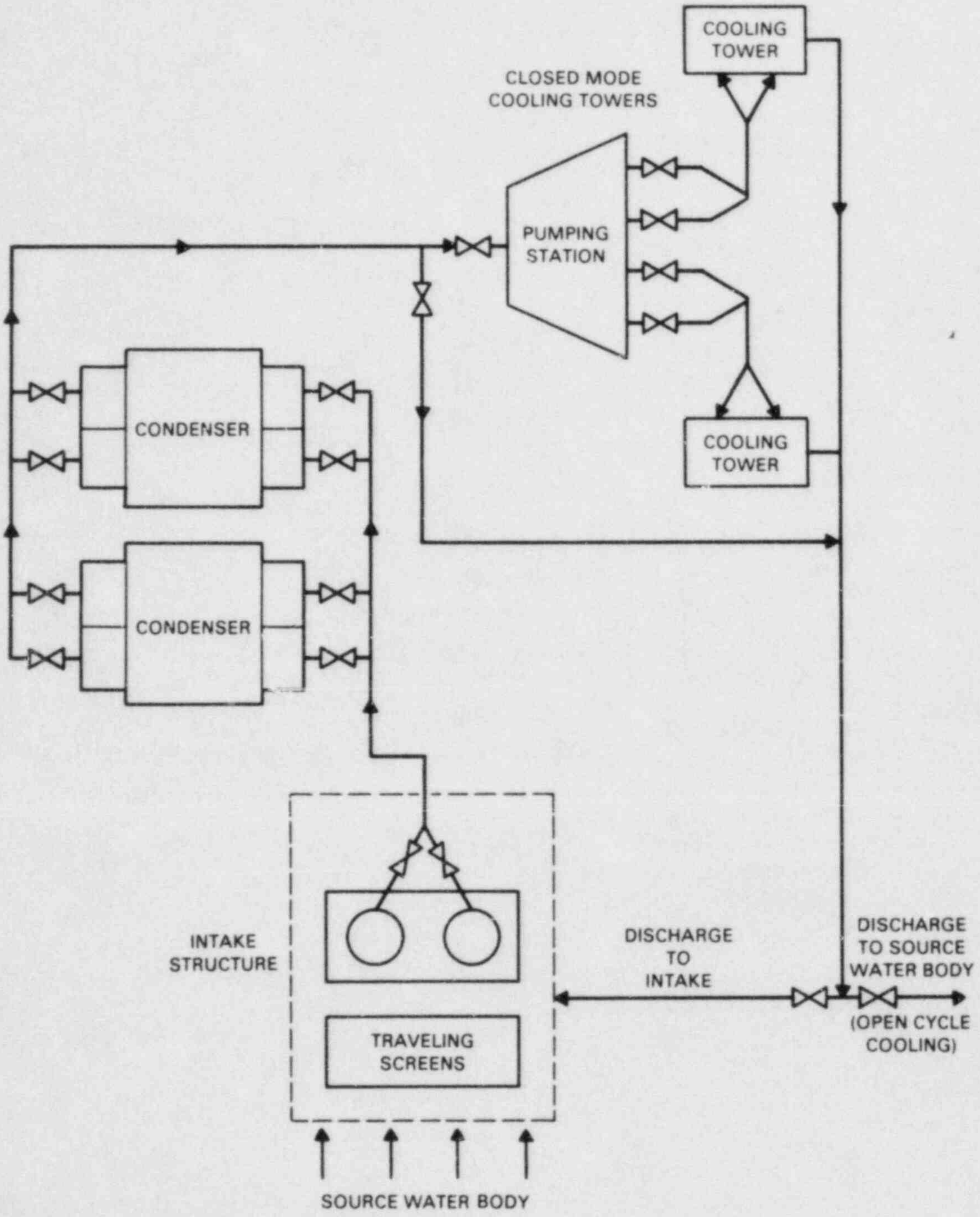

FIGURE 30. Flow Diagram of a Circulating-Water System Capable of Once-Through, Closed-Cycle, and Helper Modes of Operation

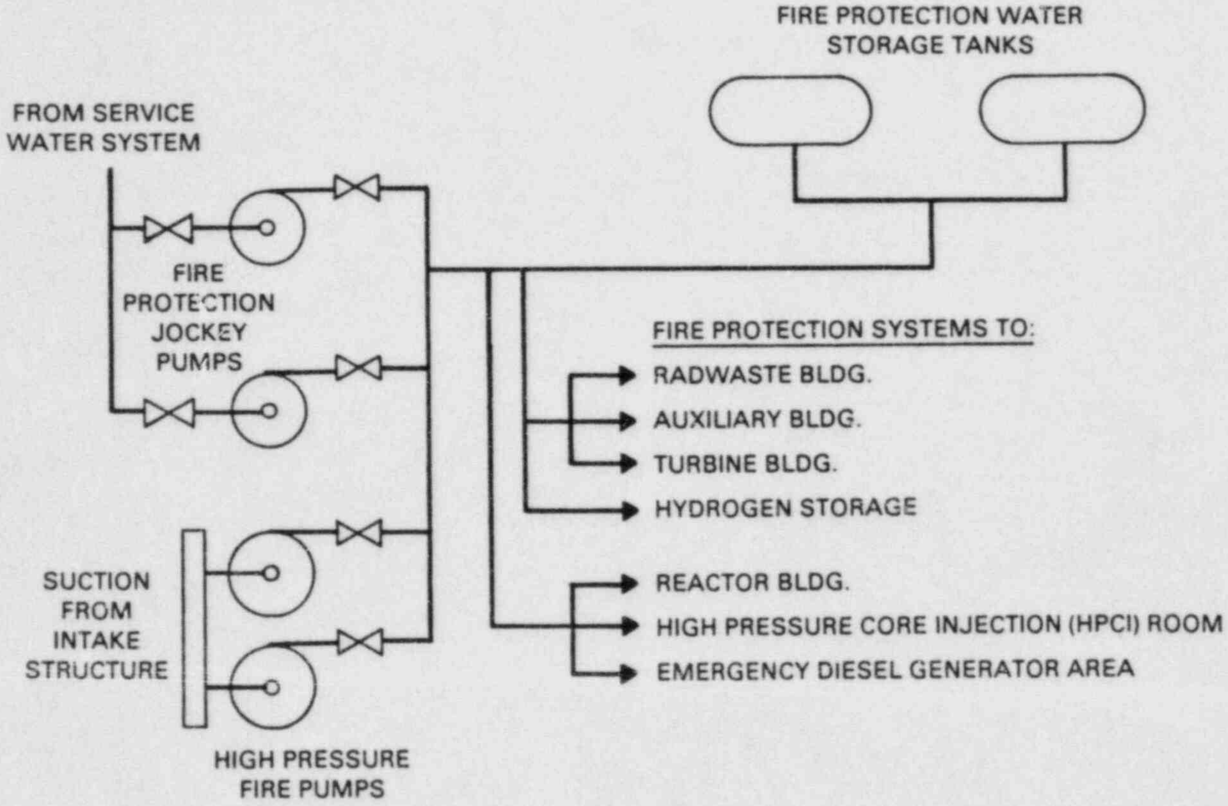

FIGURE 31. Flow Diagram of a High Pressure Fire Protection System

TABLE 11. Major Plant Areas with Fire Protection Water Systems

Nonsafety-Related Areas

Outside Areas: main transformers, service transformers, aux. transformers, startup transformers, aux. 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 reservoir, 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 area, 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 area, air handling units, and recirc pump motor-generator area.

Fuel Building: spent fuel pool heat exchangers and pumps, new fuel storage areas, railroad bay, and charcoal filtration units.

Between flow tests, which are typically conducted annually or semi-annually, most fire systems are maintained full of water.

RAW-WATER INTAKE STRUCTURES

Raw-water intake structures vary in design from plant to plant depending on environmental considerations, flow requirements of various pumps, and the judgement of the architect-engineer. Figure 32 shows a plan and elevation view of a typical intake structure design. Most plants use a common intake structure to provide water to the circulating-water pumps, service-water pumps (PWRs) or raw-cooling water pumps (BWRs), and the fire protection pumps. Two traveling screens are typically provided to each intake bay to ensure that failure of one screen does not interrupt operation. Each pump bay normally contains one circulating-water pump, one service-water pump, and one fire protection system pump. Extra bays are provided for individual circulating-water pumps if required.

Fouling is initially controlled in the intake structure. Large chunks of floating debris such as driftwood, seaweed, and ice are removed by trash racks at the opening of the intake structure. Some plants are also equipped with traversing trash rakes to remove accumulations of debris from in front of the trash racks. After entering the intake structure, water passes through self-cleaning traveling screens. These screens typically have a mesh size in the range of 4 to 13 mm (3/16 to 1/2 in.) Downstream from the service water pumps, the water passes through basket strainers (either manual or self-cleaning), which typically 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 from the strainers have come in as larvae and have found suitable conditions for growth inside the system. Fouling control must therefore address control of larvae as well as adult bivalves.

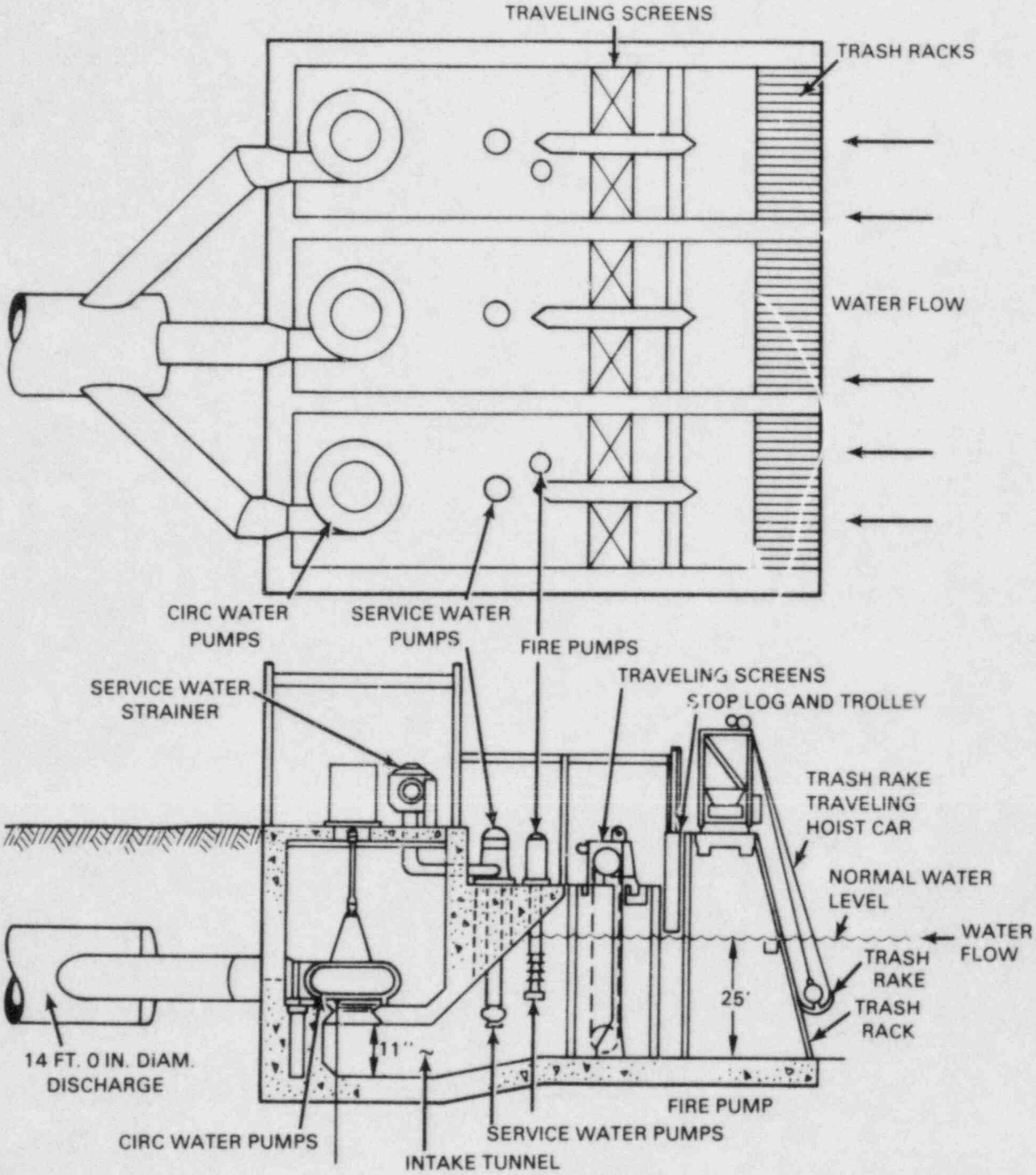

FIGURE 32. Plan and Elevation View of a Typical Shoreline Water Intake Structure

METHODS

Three main sources of information were used to prepare this report: utility responses to Inspection and Enforcement Bulletin 81-03; journal articles and technical reports; and interviews with utility personnel and power plant operators.

IE BULLETIN 81-03

On April 10, 1981, the Office of Inspection and Enforcement of NRC issued Bulletin 81-03, which requires all nuclear generation unit licensees to assess the potential for biofouling of safety-related component systems at their facilities and to describe actions taken to detect and mitigate flow blockage of these systems as a result of fouling by Asiatic clams and blue mussels. All utilities holding operating licences or construction permits were required to assess of the biofouling problem at their units.

Utilities with operating licenses were required to respond to five items in the bulletin: 1) determine if Asiatic clams or blue mussels are present in the local environment; 2) determine, by visual inspection, if fire protectionor safety-related systems are fouled by Asiatic clams or blue mussels; 3) if fouling was observed, evaluate flow rates within the safety-related systems to determine whether or not flow degradation had occurred; 4) describe methods used or planned for preventing and detecting fouling; and 5) describe the methods used to determine Items 1, 2, and 3, in addition to proposed monitoring programs to detect foulings.

Utilities with construction permits were required to respond to three items: 1) determine if Asiatic clams or blue mussels were present in the local environment; 2) if biofouling organisms were found in the local environment and plant systems had been filled with water, determine if fouling had occurred; and 3) describe the actions used to determine Items 1 and 2, in additon to monitoring programs to detect fouling. We examined the utility responses to IEB 81-03. Additionally, we used the reviews of the bulletins that was prepared by M. Masnik of NRC and Parameter, Inc. (Parameter 1982).

JOURNAL ARTICLES AND TECHNICAL REPORTS

Information on the biological characteristics of Asiatic clams, blue mussels, and American oysters was gathered from published journals, technical reports, and symposium proceedings. References to these sources are cited throughout this report and are compiled in the Literature Cited section.

PERSONNEL INTERVIEWS

Staff members from Pacific Northwest Laboratory visited and talked with power plant personnel from eight companies or utilities (Table 12). All discussions were conducted at the power plant sites except for interviews

TABLE 12. Nuclear Power Plants Visited by Pacific Northwest Laboratory Staff to Collect Information Related to Macroinvertebrate Fouling of the Service-Water System in Nuclear Power Plants

Utility and Plant	Date of Visit	Comments
Washington Public Power Supply System, WNP No. 2	March 3, 1983	Under construction; *Corbicula* in local environment
Portland General Electric, Trojan	April 14, 1983	Operating; *Corbicula* fouling in turbine bearing oil heat exchangers; surveillance and control plan in place
Arkansas Power & Light, Arkansas Nuclear One Units 1 & 2	October 3, 1983	Operating; *Corbicula* fouling; surveillance and control plan in place; on-site research in progress
Tennessee Valley Authority, Sequoyah	October 4, 1983	Operating and under construction; *Corbicula* fouling; surveillance and control plan in place
Carolina Power & Light, Brunswick	October 5, 1983	Operating; *Crassostrea* fouling; surveillance program in place; control programs being tested
Northeastern Utilities, Millstone Units 1, 2, & 3	October 6, 1983	Operating and under construction; *Mytilus* fouling; surveillance and control program in place
Boston Edison Company, Pilgrim	October 7, 1983	Operating; *Mytilus* fouling; surveillance, and control program in place
Public Service Electric & Gas, Salem	October 20, 1983	Operating; *Crassostrea* and *Mytilus* fouling; surveillance and control program in place

conducted with personnel at the Salem Power Plant in Salem, New Jersey. We discussed the utilities' response to IEB 81-03, the utilities' current surveillance and control program, and any on-going research programs at the site. A common list of questions was used to guide the discussions and provide uniformity among interviews (see Appendix).

REFERENCES

Abbe, G. R. 1980. "Nonradiological Studies of Tray-held Oysters, *Crassostrea virginica*, in the Vicinity of the Calvert Cliffs Nuclear Plant in Chesapeake Bay, 1970-1979." *J. Shellfish Res.* 1:107.

Abbe, G. R. 1982. "Growth, Mortality, and Copper-Nickel Accumulation by Oysters (*Crassostrea virginica*) at the Morgantown Steam Electric Station on the Potomac River, Maryland." *J. Shellfish Res.* 2:3-13.

Aldridge, D. W., and R. F. McMahon. 1978. "Growth, Fecundity, and Bioenergetics in a Natural Population of the Asiatic Freshwater Clam, *Corbicula manilensis* Philippi, form North Central Texas." *J. Mollusc. Studies* 44:49-70.

Allen, J. A., M. Cook, D. J. Jackson, S. Preston, and E. M. Worth. 1976. "Observations on the Rate of Production and Mechnaical Properties of the Bypass Threads of *Mytilus edulis* L." *J. Moll. Studies* 42:279-289.

Almada-Villela, P. C., J. Davenport, and L. D. Gruffydd. 1982. "The Effects of Temperature on Shell Growth of Young *Mytilus edulis* L." *J. Exp. Mar. Biol. Ecol.* 59:275-288.

Anonymous. 1975. "Heated Water from a Power Plant Put to Good Use by Oyster Farm." *Sea Tech.* 16:21-22.

Avolizi, R. J. 1971. *Biomass Turnover in Natural Populations of Viviparous sphaerid Clams: Interspecific and Intraspecific Comparisons of Growth, Fecundity, Mortality, and Biomass Production*. Ph.D. Dissertation, Syracuse University, Syracuse, New York.

Bacon, H. E. 1978. "Corrosion." In *Mark's Standard Handbook for Mechanical Engineers*, pp. 6.106-117. 8th ed. McGraw Hill, New York, New York.

Bahr, L. M., and R. E. Hillman. 1967. "Effects of Repeated Shell Damage on Gametogenesis in the American Oyster, *Crassostrea virginica* (Gmelin)." *Proc. Nat. Shellfish Assoc.* 57:59-62.

Bayne, B. L. 1964. "Primary and Secondary Settlement in *Mytilus edulis* L. (Mollusca)." *J. Anim. Ecol.* 33:513-523.

Bayne, B. L. 1965. "Growth and Delay of Metamorphosis of the Larvae of *Mytilus edulis* (L.)." *Ophelia* 2:1-47.

Bayne, B. L. 1972. "Some Effects of Stress in the Adult on the Larval Development of *Mytilus edulis*." *Nature* 237:459.

Bayne, B. 1975. "Reproduction in Bivalve Molluscs under Environmental Stress." In *Physiological Ecology of Estuarine Organisms*, ed. F. J. Vernberg, pp. 259-277. University of South Carolina Press, Columbia, South Carolina.

Bayne, B. L. P. A. Gabbot, and J. Widdows. 1975. "Some Effects of Stress in the Adult on the Eggs and Larvae of *Mytilus edulis* L." *J. Mar. Biol. Assoc. U.K.* 55:675-689.

Bayne, B. L., and J. Widdows. 1978. "The Physiological Ecology of Two Populations of *Mytilus edulis* L." *Oecologia* 37:137-162.

Beaven, G. F. 1954. "Various Aspects of Oyster Setting in Maryland." *Proc. Nat. Shellfish Assoc.* 45:29-37.

Brenko, M. Hrs., and A. Calabrese. 1969. "The Combined Effects of Salinity and Temperature on Larvae of the Mussel *Mytilus edulis*." *Mar. Biol.* 4:224-226.

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.

Britton, J. C., and B. Morton. 1982. "A Dissection Guide, Field and Laboratory Manual for the Introduced Bivalve *Corbicula fluminea*." *Malacological Rev.*, Supplement 3.

Burch, J. Q. 1944. "Checklist of West American Mollusks, Family *Corbiculidae*. *Minutes of the Conchological Club of Southern California* 36:18.

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

Calabrese, A., R. S. Collier, D. A. Nelson and J. R. MacInnes. 1973. "The Toxicity of Heavy Metals to Embryos of the American Oysters, *Crassostrea virginica*." *Mar. Biol.* 18:162-166.

Calabrese, A., and H. C. Davis. 1966. "The pH Tolerance of Embryos and Larvae of *Mercenaria mercenaria* and *Crassostrea virginica*." *Biol. Bull.* 131:427-436.

Calabrese, A., and H. C. Davis. 1969. "Spawning of the American Oyster, *Crassostrea virginica*, at Extreme pH Levels." *Veliger* 11:235-236.

Capuzzo, J. M. 1979. "The Effect of Temperature on the Toxicity of Chlorinated Cooling Waters to Marine Animals: A Preliminary Review." *Mar. Pollut. Bull.* 10:45-47.

Carriker, M. R., and P. E. Palmer. 1979. "Ultrastructural Morphogenesis of Prodissoconch and Early Dissoconch Valves of the Oyster *Crassostrea virginica*." *Proc. Nat. Shellfish. Assoc.* 69:103-128.

Chanley, P. E. 1957. "Survival of Some Juvenile Bivalves in Water of Low Salinity." *Proc. Nat. Shellfish. Assoc.* 48:52-65.

Chanley, P. E., and J. D. Andrews. 1971. "Aids for Identification of Bivalve Larvae of Virginia." *Malacologia* 11:45-119.

Chipperfield, P. N. J. 1953. "Observations on the Breding and Settlement of *Mytilus edulis* (L.) in British Waters." *J. Mar. Biol. Assoc. U.K. 32*:449-476.

Dauble, D. D., D. S. Daley, and C. S. Abernethy. 1984. "Factors Affecting Growth and Survival of the Asiatic Clam, *Corbicula sp.* under Controlled Laboratory Conditions." *Proceedings of the ASTM 7th Symposium on Aquatic Toxicology.* American Society of Testing and Materials, Philadelphia, Pennsylvania.

Davis, H. C., 1958. "Survival and Growth of Clam and Oyster Larvae at Different Salinities." *Biol. Bull.* 114:296-307.

Davis, H. C., and A. Calabrese. 1964. "Combined Effects of Temperature and Salinity on Development of Eggs and Growth of Larvae of *M. Mercenaria* and *C. virginica*." *Fish. Bull.* 63:643-655

Davis, H. C., and P. E. Chanley. 1955. "Spawning and Egg Production of Oysters and Clams." *Proc. Nat. Shellfish. Assoc.* 46:40-51.

DeBlok, J. W., and H. J. M. Geelen. 1958. "The Substratum Required for the Settling of Mussels (*Mytilus edulis* L.)." *Arch. Néerlandaises.* Jubilee Vol. 446-460.

Drake, R. C. 1977. "Increasing Heat Exchanger Efficiency Through Continuous Mechanical Tube Maintenance." In *Biofouling Control Procedures*, ed. L. D. Jensen, pp. 43-53. Marcel Dekker, Inc., New York, New York.

Drinnan R. E. 1969. "The Effect of Early Fouling of Shell Surfaces on Oyster Spatfall." *Proc. Nat. Shellfish. Assoc.* 59:2

Eng. L. L. 1979. "Population Dynamics of the Asiatic Clam, *Corbicula fluminea* (Muller), in the Concrete-lined Delta-Mendota Canal of Central California." In *Proceedings, First Inrernational Corbicula Symposium*, ed. J. C. Britton, pp. 39-68. Texas Christian University Research Foundation, Fort Worth, Texas.

Engle, J. B., and V. L. Loosanoff. 1944. "On Season of Attachment of Larvae of *Mytilus edulis* Linn." *Ecology* 25:433-440.

Foster, T. D. 1932. "Observations on the Life History of a Fingernail Clam of the Genus *Sphaerium*." *J. Morph.* 53:473-497.

Gabbott, P. A., and B. L. Bayne. 1973. "Biochemical Effects of Temperature and Nutritive Stress on *Mytilus edulis* L." *J. Mar. Biol. Assoc. U.K.* 53:269-286.

Galtsoff, P. S. 1957. "The Past and Future of Oyster Resarch." *Proc. Nat.Shellfish. Assoc.* 48:8-22.

Galtsoff, P. S. 1964. "The American Oyster *Crasssostrea virginica* Gmelin." *Fish. Bull.* 64:1-480.

Gardner, J. A. Jr., W. R. Woodall, Jr., A. A. Stoats, Jr., and J. F. Napoli. 1976. "The Invasion of the Asiatic Clam *Corbicula manilensis* (Philippi) in the Altahama River, Georgia." *Nautilus* 90:117-125.

Gillmore, G. H., S. M. Ray, and D. V. Aldrich. 1975. *Growth and Mortality of Two Groups of Oysters, (Crassostrea virginica Gmelin), Maintained in Cooling Water at an Estuarire Electric Power Generating Station.* TAMU-SG-75-207, Texas A&M University, Galveston, Texas.

Glaus, K. J. 1968. "Factors Influencing the Production of Byssus Threads in *Mytilus edulis*." *Biol. Bull.* 135:420.

Gonzales, J. G., and P. Yevich. 1976. "Responses of an Estuarine Population of the Blue Mussel *Mytilus edulis* to Heated Water from a Steam Generating Plant." *Mar. Biol.* 34:177-189.

Goss, L. B., and C. Cain, Jr. 1977. "Power Plant Condenser and Service Water System Fouling by *Corbicula*, the Asiatic Clam." In *Biofouling Control Procedures*, ed. L. D. Jensen, pp. 11-17. Marcel Dekker, Inc., New York.

Goss, L. B., J. M. Jackson, H. B. Flora, B. G. Isom, C. Gooch, S. A. Murray, C. G. Burton, and W. S. Bain. 1979. "Control Studies on *Corbicula* for Steam-electric Generating Plants." In *Proceedings, First International Corbicula Symposium*, ed. J. C. Britton, pp. 139-151. Texas Christian University Research Foundation, Fort Worth, Texas.

Gunter, G. 1979. "The Gift Principle and the Morphology of Oyster Reefs." *Proc. Nat. Shellfish Assoc.* 69:1-5

Hayes, P. F., and R. W. Menzel. 1981. "The Reproductive Cycle of Early Setting *Crassostrea virginica* (Gmelin) in the Northern Gulf of Mexico, and Its Implications for Population Recruitement." *Biol. Bull.* 160:80-88.

Heard, W. H. 1965. "Comparative Life Histories of North American Pill Clams (Sphaeriidae:Pisidium)." *Malacologia* 2:381-411.

Heard, W. H. 1962. "The Sphaeriidae (Mollusca: Pelecypoda) of the North American Great Lakes." *Am. Midland Nat.* 67:194-198.

Heinsohn, G. E. 1958. *Life History and Ecology of the Freshwater Clam, Corbicula fluminea*. M.S. Thesis, University of California, Berkeley.

Hidu, H. 1978. "Setting of Estuarine Invertebrates in Delaware Bay, New Jersey, Related to Intertidal-Subtidal Gradients." *Int. Revue Ges. Hydrobiol.* 63:637-661.

Hidu, H., W. H. Roosenberg, K. G. Drobeck, A. J. McErlean, and J. A. Mihursky. 1974. "Thermal Tolerance of Oyster Larvae, *Crassostrea virginica* Gmelin, as Related to Power Plant Operation." *Proc. Nat. Shellfish Assoc.* 64:102-110.

Hidu, H., F. P. Veitch, Jr., and P. E. O'Brien. 1969. "Gregarious Setting in the American Oyster." *Proc. Nat. Shellfish. Assoc.* 60:4

Hidu, H., W. G. Valleau, and F. P. Veitch. 1978. "Gregarious Setting in European and American Osyters - Response to Surface Chemistry vs. Waterborne Pheromones." *Proc. Nat. Shellfish Assoc.* 68:11-16.

Hildreth, D. I. 1976. "The Influence of Water Flow Rate on Pumping Rate in *Mytilus edulis* Using a Refined Direct Measurement Apparatus." *J. Mar. Biol. Assoc. U.K.* 56:311-319.

Hopkins, S. H. 1954. "Oyster Setting on the Gulf Coast." *Proc. Nat. Shellfish Assoc.* 45:52-55.

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

Ingle, R. M. 1951. "Spawning and Setting of Oysters in Relation to Seasonal Environmental Changes." *Bull. Mar. Sci. Gulf. Carib.* 1:111-135.

Ingle, R. M., and C. E. Dawson, Jr. 1952. "Growth of the American Oyster *Crassostrea virginica* (Gmelin) in Florida Waters." *Bull. Mar. Sci. Gulf. Carib.* 2:393:404

Jorgensen, D. B. 1976. "Growth Efficiencies and Factors Controlling in Some Mytilid Bivalves, Especially *Mytilus edulis* L.: Review and Interpretation." *Ophelia* 15:175-192.

Kastendiek, J., S. C. Schroeter, and J. Dixon. 1981. "The Effect of the Seawater Cooling System of a Nuclear Generating Station on the Growth of Mussels in Experimental Populations." *Mar. Pollut. Bull.* 12:402-407.

Kennedy, A. V., and H. I. Battle. 1964. "Cyclic Changes in the Gonad of the American Oyster, *Crassostrea virginica* (Gmelin)." *Canadian J. Zool.* 42:305-321.

Kirchman, D., and R. Mitchell. 1981. "A Biochemical Mechanism for Marine Biofouling." In *Oceans '81 Conference Record*, Vol. 1, pp. 537-541. The Institute of Electrical and Electronics Engineers, New York.

Krantz, G. E., and J. V. Chamberlin. 1978. "Bue Crab Predation on Cultchless Oyster Spat." *Proc. Nat. Shellfish. Assoc.* 68:38:41.

Ladle, M., and F. Baron. 1969. "Studies on Three Species of Pisidium from a Chalk Stream." *J. Animal Ecol.* 38:407-413.

Loosanoff, V. L. 1942. "Seasonal Gonadal Changes in the Adult Oysters, *Ostrea virginica*, of Long Island Sound." *Biol. Bull.* 82:195-206.

Loosanoff, V. L., H. C. Davis, and P. E. Chanley. 1966. "Dimensions and Shapes of Larvae of Some Marine Bivalve Mollusks." *Malacologia*. 4:351-435.

Loosanoff, V. L. 1949. "Methods for Supplying a Laboratory with Warm Seawater in Winter." *Science* 110:192-193.

Loosanoff, V. L. 1952. "Behavior of Oysters at Low Salinities." *Conv. Address., Nat. Shellfish. Assoc.* 135-151.

Loosanoff, V. L. 1958a. "Use of Plastics for Collecting Oyster Set." *Comm. Fish. Rev.* 20:52-54.

Loosanoff, V. L. 1958b. "Some Aspects of Behavior of Oysters at Different Temperatures." *Biol. Bull.* 114:57-70.

Loosanoff, V. L. 1965. *The American or Eastern Oyster.* U.S. Department of the Interior, Fish and Wildlife Service, Circular 205.

Loosanoff, V. L. 1966. "Time and Intensity of Setting of the Oyster *Crassostrea virginica*, in Long Island Sound." *Biol. Bull.* 130:211-227.

Loosanoff, V. L. and H. C. Davis. 1958. "Temperature Requirements for Maturation of Gonads of Northern Oysters." *Biol. Bull.* 103:80-96.

Loosanoff, V. L. and H. C. Davis. 1963. "Rearing of Bivalve Mollusks." Volume 1 of *Advances in Marine Biology*, ed. F. S. Russell, pp. 1-136. Academic Press, New York.

Loosanoff, V. L., and C. A. Nomejko. 1949. "Growth of Oysters, *O. virginica*, during Different Months." *Biol. Bull.* 97:82-94.

Lutz, R. H., H. Hindu, and K. G. Drobeck. 1970. "Acute Temperature Increase as a Stimulus to Setting in the American Oyster, *Crassostrea virginica* (Gmelin)." *Proc. Nat. Shellfish Assoc*. 60:68-71.

Maas Geesteranus, R. A. 1942. "On the Formation of Banks by *Mytilus edulis* L." *Arch. Néerlandaises Zool.* 6:283-325.

MacInnes, J. R., and A. Calabrese. 1978. "Response of Embryos of the American Oyster, Crassostrea virginica, to Heavy Metals at Different Temperatures." In Physiology and Behavior of Marine Organisms, ed. D. S. McLusky and A. J. Berry, pp. 195-201. Pergamon Press, Elmsford, New York.

MacInnes, J. R., and A. Calabrese. 1979. "Combined Effects of Salinity, Temperature, and Copper on the Embryos and Early Larvae of the American Oyster, Crassostrea virginica." Arch. Env. Contam. Toxicol. 8:553-562.

MacKenzie, C. L., Jr. 1975. "Development of a Program to Rehabilitate the Oyster Industry of Prince Edward Island." Mar. Fish. Rev. 37:21-35.

MacKenzie, C. L., Jr. 1977. "Development of an Aquacultural Program for Rehabilitation of Damaged Oyster Reefs in Mississippi." Mar. Fish. Rev. 39:1-13.

MacKenzie, C. L., Jr. 1981. "Biotic Potential and Environmental Resistence in the American Oyster (Crassostrea virginica) in Long Island Sound." Aquaculture 22:229-268.

Mackie, G. L., S. U. Qadri, and A. H. Clark. 1976. "Reproductive Habits of Four Populations of Musculium securis (Bivalvia:Sphaeriidae) near Ottawa, Canada." Nautilus 90:76-86.

MacLean, S. A., A. C. Longwell, and W. J. Blogoslawski. 1973. "Effect of Ozone-treated Sewater on the Spawned, Fertilized, Meiotic, and Cleaving Eggs of the Commercial American Oyster." Mutat. Res. 21:282-285.

MacPhee, D. 1983. "A Mechanical Strainer Design for Corbicula Fouling Protection in the Service Water System at Arkansas Nuclear One, Unit 2." Presented at the Second International Corbicula Symposium, June 21-24, 1983., Little Rock, Arkansas.

Mattice, J. S., and L. L. Dye. 1976. "Thermal Tolerance of the Adult Asiatic Clam." In Thermal Ecology II, G. W. Esch and R. W. McFarlane, pp. 130-135. ERDA Symposium Series, CONF-750425, National Technical Information Service, Springfield, Virginia.

Mattice, J. S., R. B. McLean, and M. B. Burch. 1982. Evaluation of Short-term Exposure to Heated Water and Chlorine for Control of the Asiatic Clam (Corbicula fluminea). ORNL-TM-7808. Prepared for the U.S. Department of Energy by Oak Ridge National Laboratory, Oak Ridge, Tennessee.

McNulty, J. K. 1953. "Seasonal and Vertical Patterns of Oyster Setting Off Wadmalaw Island, South Carolina." Bears Bluff Laboratories, Contr. 15.

Merrill, A. S., and K. J. Boss. 1966. "Benthic Ecology and Faunal Change Relating to Oysters from a Deep Basin in the Lower Patuxent River, Maryland." Proc. Nat. Shellfish Assoc. 56:81-87.

Moore, D. R., and D. J. Reish. 1969. "Studies on the *Mytilus edulis* Community in Alamitos Bay, California: IV. Seasonal Variation in Gametes from Different Regions in the Bay." *Veliger* 11:250-255.

Myint, V. M, and P. A. Tyler. 1982. "Effects of Temperature, Nutritive and Metal Stressors on the Reproductive Biology of *Mytilus edulis*." *Mar. Biol.* 67:209-223.

Newell, R. I. E., T. J. Hillbish, R. K. Koehn, and C. J. Newell. 1982. "Temporal Variation in the Reproductive Cycle of *Mytilus edulis* L. (Bivalvia, Mytilidae) from Localities on the East Coast of the United States." *Biol. Bull.* 162:229-310.

Newkirk, G. F., L. E. Haley, D. L. Waugh, and R. Doyle. 1977. "Genetics of Larvae and Spat Growth Rate in the Oyster *Crassostrea virginica*." *Mar. Biol.* 41:49-52.

Pearce, J. B. 1969. "Thermal Addition and the Benthos, Cape Cod Canal." *Chesapeake Sci.* 10:227-233.

Pennak, R. W. 1978. *Freshwater Invertebrates of the United States*. John Wiley and Sons, New York, New York.

Price, H. A. 1980. "Seasonal Variation in the Strength of Byssal Attachment of the Common Mussel *Mytilus edulis* L." *J. Mar. Biol. Assoc. U.K.* 60:1035-1037.

Price, H. A. 1982. "An Analysis of Factors Determining Seasonal Variation in the Byssal Attachment Strength of *Mytilus edulis*." *J. Mar. Biol. Assoc. U.K.* 62:147-155.

Price, A. H., II, C. T. Hess, and C. W. Smith. 1976. "Observations of *Crassostrea virginica* Cultured in the Heated Effluent and Discharged Radionuclides of a Nuclear Power Reactor." *Proc. Nat. Shellfish Assoc.* 66:54-67.

Reish, D. J. 1964. "Studies on the *Mytilus edulis* Community in Alamitos Bay, California: I. Development and Destruction of the Community." *Veliger* 6:124-131.

Richardson, L. B., D. T. Burton, and A. M. Stavola. 1982. "A Comparison of Ozone and Chlorine Toxicity to Three Life Stages of the American Oyster *Crassostrea virginica*." *Mar. Env. Res.* 6:99-113.

Ritche, T. P., and R. W. Menzel. 1969. "Influence of Light on Larval Settlement of American Oysters." *Proc. Nat. Shellfish. Assoc.* 59:116-120.

Roberts, D. 1975. "The Effect of Pesticides on Byssus Formation in the Common Mussel, *Mytilus Edulis*." *Environ. Pollut.* 8:241-254.

Roberts, M. H., R. R. J. Diaz, M. E. Bender, and R. J. Huggett. 1975. "Acute Toxicity of Chlorine to Selected Estuarine Species." J. Fish. Res. Bd. Canada 32:2525-2528.

Roberts, M. H., and R. A. Gleeson. 1978. "Acute Toxicity of Bromochlorinated Sea Water to S[illegible]ected Estuarine Species with a Comparison to Chlorinated Sea Water Toxi[illegible]" Mar. Env. Res. 1:19-30.

Roosenburg, W. H., J. C. Rhode[illegible] R. M. Block, V. S. Kennedy, S. R. Gullans, S. M. Vreenegoor, A. Ro[illegible]kranz, and C. Collette. 1980. "Effects of Chlorine-produced Oxidants on Survival of Larvae of the Oyster Crassostrea virginica." Mar. Ecol. - Prog. Ser. 3:93-96.

Scheer, B. T. 1945. "The Development of Marine Fouling Communities." Biol. Bull. 89:103-121.

Seed, R. 1969a. "The Ecology of Mytilus edulis L. (Lamellibranchiata) on Exposed Rocky Shores. I. Breeding and Settlement." Oecologia (Berl.). 3:277-316.

Seed, R. 1969b. "The Ecology of Mytilus edulis L. (Lamellibranchiata) on Exposed Rocky Shores. I. Growth and Mortality." Oecologia (Berl.). 3:317-350.

Seed, R. 1976. "Ecology." In Marine Mussels: Their Ecology and Physiology, ed. B. L. Bayne, pp. 13-65. Cambridge University Press, Cambridge, England.

Seliger, H. H., J. A. Boggs, R. B. Rivkin, W. H. Biggley, and K. R. H. Aspden. 1982. "The Transport of Oyster Larvae in an Estuary." Mar. Biol. 71:57-72.

Sergy, G. A., and J. W. Evans. 1975. "The Steelement and Distribution of Marine Organisms Fouling a Seawater Pipe System." Veliger 18:87-92.

Shaw, R., D. C. Arnold, and W. B. Stallworthy. 1970. "Effects of Light on Spat Settlement of the American Oyster (Crassostrea virginica)." J. Fish. Res. Bd. Canada 27:743-748.

Shaw, W. N. 1967. "Seasonal Fouling and Oyster Setting on Asbestos Plates in Broad Creek, Tabot County, Maryland, 1963-1965." Chesapeake Sci. 8:228-236.

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

Sickel, J. B. 1976. "Population, Growth and Productivity of Corbicula manilensis (Philippi) in the Altamaha River, Georgia (Bivalva: Corbiculidai)." ASB Bulletin 23:96.

Sinclair, R. M. 1971. "Annotated Bibliography on the Exotic Bivalve Corbicula in North America, 1900-1971." *Sterkiana* 43:11-18.

Sinclair, R. M., and B. G. Isom. 1961. *A Preliminary Report on the Introduced Asiatic Clam Corbicula in Tennessee.* Stream Pollution Control Board, Tennessee Department of Public Health, Cordell Hull Building, Nashville.

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.

Stromgren, T. 1976a. "Growth Patterns of *Mytilus edulus* in Relation to Individual Variation, Light Conditions, Feeding and Starvation." *Sarsia* 60:25-40.

Stromgren, T. 1976b. "Length Growth of *Mytilus edulis* (Bivalvia) in Relation to Photoperiod, Irradiance, and Spectral Distributionof Light." *Sarsia* 61:31-40.

Theisen, B. F. 1972. "Shell Cleaning and Deposit Feeding in *Mytilus edulis* L. (Bivalvia)." *Ophelia* 10:49-55.

Theisen, B. F. 1973. "The Growth of *Mytilus edulis* L. (Bivalvia) from Disko and Thule District, Greenland." *Ophelia* 12:59-77.

Thompson, R. J., and B. L. Bayne. 1974. "Some Relationships Between Growth, Metabolism and Food in the Mussel, *Mytilus edulis*." *Marine Biol.* 27:317:326.

Thompson, R. J., N. A. Ratcliff, and B. L. Bayne. 1974. "Effects of Starvation on Structure and Function in the Digestive Gland of the Mussel (*Mytilus edulis* L.)." *J. Mar. Biol. Assoc. U.K.* 54:699-712.

Tinsman, J. C., and D. L. Maurer. 1974. "Effects of a Thermal Effluent on the American Oyster." In *Thermal Ecology*, eds. J. W. Gibbons and R. R. Sharitz, pp. 223-236. National Technical Information Service, Springfield, Virginia.

Vahl, O. 1973. "Pumping and Oxygen Consumption Rates of *Mytilus edulis* L. of Different Sizes." *Ophelia* 12:45-52.

Van Winkle, W., Jr. 1970. "Effect of Environmental Factors on Byssal Thread Formation." *Mar. Biol.* 7:143-148.

Veitch, F. P., and H. Hidu. 1971. "Gregarious Setting in the American Oyster *Crassostrea virginica* Gmelin: I. Properties of a Partially Purified 'Setting Factor.'" *Chesapeake Sci.* 12:173-178.

Villadolid, D. V., and F. G. del Rosario. 1930. "Some Studies on the Biology of Tulla (Corbicula manilensis), a Common Food Clam of Laguna de Bay and Its Tributaries." Phillipine Agricult. 19:355-382.

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.

Wolfson, A. A. 1974. Some Effects of Increased Temperature on the Settlement and Development of a Marine Community in the Laboratory. UC-1MR Reference No. 74-13, University of California, Institute of Marine Resources, La Jolla, California.

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

Young, J. S., and A. W. Frame. 1976. "The Effects of a Power Plant Effluent on Estuarine Epibenthic Fauna." Internationale Revue der Gesamten Hydrobiologie 61:37-61.

APPENDIX

QUESTIONS USED TO INTERVIEW POWER PLANT PERSONNEL

Name: ______________________________

Company: ___________________________

1. For systems where biofouling has occurred,
   a. Name of system and component (send design sketch if possible)
   b. Species of mollusk
   c. Flow velocity
   d. Pipe diameter
   e. Water temperature
   f. Is this a safety-related system?
   g. Is this system used intermittently?

2. In your opinion, what factors have caused biofouling at your plant.

   Possible factors:

   a. Flow velocity (or lack of flow)

   b. Water temperature

   c. Water chemistry

   d. Other

3. If Asiatic clams (Corbicula sp.), blue mussels (Mytilus edulis), or American oysters (Crassostrea virginica) are present in the immediate vicinity of your plant and biofouling has not occurred, what do you believe are the reasons for the lack of biofouling?

   a. Control procedures

   b. Natural inhibitors

   c. Other

4. Of the systems or components which have fouled, are there similar or identical systems or components which have not become fouled? If so, why, in your opinion, has this occurred?

5. Do you have a program which monitors aquatic organisms in the vicinity of the plant intake?

   a. Sampling method

   b. Sampling frequency

   c. Population density of biofouling organimsm

6. Describe your water intake and source for auxiliary service-water systems.

   a. Location relative to discharge

   b. Types and placement of screens

   c. Intake forebay configuration (send diagram or design sketch if possible)

d. Seasonal temperature extremes of water source

e. Seasonal extremes of water depth and flow rate

f. If water source is a lake, what is the maximum amount of shoreline exposed during low water periods?

g. Type of water treatment procedures used at intake

7. Are there certain components or system sizes or arrangements which seem to promote biofouling?

    a. Piping geometry

        1. Low spots in piping loops

        2. Dead legs

        3. Pipe diameter

        4. Flow velocity

        5. Frequency of use

b. Intake structures
    1. Water-boxes
    2. Pumphouse forebays

c. Specific types of components
    1. Valve
    2. Pump
    3. Screen
    4. Heat exchangers

d. Materials
    1. Concrete
    2. Steel
    3. Plastics

e. Other

8. Are there certain system component or geometries which seem to inhibit biofouling?

   a. Piping geometry

   b. Intake structures

   c. Specific types of components

   d. Materials

      1. Plastic

      2. Nickel/copper bearing steels

      3. Bituminous coatings

      4. Other

   e. Other

9. Are other types of fouling known to promote or inhibit biofouling at your plants?

   a. Corrosion products

   b. Silt or mud

   c. Pollution in water source

   d. Other

10. Is biofouling known to be seasonal at your plant? If so, when is it most severe? When are mollusk spawning seasons?

11. What are the first noticeable indications that a system is becoming biofouled?

12. How do you detect biofouling?

    a. Flow tests

    b. Increase pressure drop

    c. Visual inspection

    d. Heat exchanger heat transfer coefficient

    e. Degraded performance of water system

    f. Other

13. How do you control biofouling? In you opinion, how effective is it?

    a. Asiatic clams

    b. Blue mussels

    c. American oysters

d. Slime

e. Silt

f. Other

14. Do you use precautionary measures to reduce the biofouling potential in systems which are used occasionally?

    a. Chlorinate

    b. Drain system

    c. Flush and fill with demineralized water

    d. Other

15. Is biofouling a potential problem in your fire protection system?

    a. What is your water source?

    b. System maintenance after testing or use

        1. Drain system

        2. Chlorinate

        3. Flush and fill with demineralized water

        4. Other

16. Has biofouling occurred during or immediately following downtimes? If so, why in your opinion has this occurred?

    a. Do service-water systems remain in operation during downtimes?

    b. Do your technical specifications for these systems require the same surveillance during downtimes and operation?

17. Can you think of any circumstances where some action or procedure has or could result in more biofouling than normal?

18. Has your utility sponsored any research or written any papers (published papers, internal reports, memos, etc.) that we might obtain which further explain your biofouling experience?

    a. Title

    b. Ordering information

    c. Attach copy if available.

DISTRIBUTION

No. of
Copies
OFFSITE

20 Frank Swanberg
Senior Project Manager
Waste Management Branch
Division of Radiation Programs
and Earth Sciences
Office of Nuclear Regulatory
Research
U.S. Nuclear Regulatory Comm.
Washington, D.C. 20555

U.S. Nuclear Regulatory Commission
Division of Technical Information
and Document Control
7920 Norfolk Avenue
Bethesda, MD 20014

Charlie Adams
Arkansas Power & Light
Little Rock, AR 72203

Louis J. Anastasia
Commonwealth Edison
P.O. Box 767
Chicago, IL 60690

William J. Armstrong
Boston Edison Co.
Nuclear Operations Dept.
Braintree, MA 02184

John Balletto
Public Service Electric & Gas
Licensing & Regulation
P.O. Box 236
Hancock's Bridge, NJ 08038

Christopher Benedict
Carolina Power and Light
Brunswick Biological Lab
P.O. Box 10429
Southport, NC 28461

Harry F. Bernhard
Commonwealth Edison
72 West Adams Room 1700
Chicago, IL 60690

Dr. Joe Britton
Dept. of Biology
Texas Christian University
P.O. Box 32916
Fort Worth, TX 76129

Winston Chow
Electric Power Research Institute
P.O. Box 10412
Palo Alto, CA 94303

James J. Hall
Environmental Lab
Duke Power Co.
Route 4, Box 531
Huntsville, NC 28078

Gary Johnson
Northeast Utilities Envir. Lab
P.O. Box 128
Waterford, CT 06385

Joe Johnson
Tennessee Valley Authority
1110 CST-2
Chattanooga, TN 37401

Louise R. Kraemer
Dept. of Zoology
Univ. of Arkansas
Fayetteville, AR 72701

Jack Mattice
Electric Power Research Inst.
P.O. Box 10412
Palo Alto, CA 94303

Bob McMahon
Dept. of Biology
Univ. Texas Arlington
Box 19498
Arlington, TX 76019

Walter J. Meiers
Detroit Edison
H-127 WSC
2000 Second Avenue
Detroit, MI 48226

Leo P. Modenos
1100 Circle 75 Parkway
Suite 1500
Atlanta, GA 30339

Gordon Rich
Trojan Power Plant
P.O. Box 439
Ranier, OR 97048

Robert L. Roy, Jr.
Celanese Fibers Co.
P.O. Box 767
Narrows, VA 24124

Louis Scotton
Boston Edison Co.
25 Braintree Hill Office Park
Braintree, MA 02184

Terry Smith
The Dalles, John Day Project
P.O. Box 564
The Dalles, OR 97058

James A. Smithson
Illinois Power Company
500 S. 27th Street
Decatur, IL 62522

Pam Witt
Tennessee Valley Authority
1110 CST-2
Chattanooga, TN 37401

Robert M. West
Arkansas Power and Light
P.O. Box 551
Little Rock, AR 72203

ONSITE

(50) Pacific Northwest Laboratory

K. A. Byers (4)
P. M. Daling (5)
C. H. Henager (5)
K. I. Johnson (5)
D. H. McKenzie
D. A. Neitzel (10)
C. M. Novich
T. L. Page (7)
J. A. Strand
W. L. Templeton
B. E. Vaughan
R. E. Wildung
J. A. Young
Publishing Coordination (2)
Technical Information (5)

NRC FORM 335
(2-84)
NRCM 1102,
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-4070
PNL-5300
Vol. 1

2. TITLE AND SUBTITLE
Bivalve Fouling of Nuclear Power Plant Service-Water Systems. Volume 1: Correlation of Bivalve Biological Characteristics and Raw-Water System Design

3. LEAVE BLANK

4. DATE REPORT COMPLETED

MONTH	YEAR
November	1984

5. AUTHOR(S)
D. A. Neitzel
K. I. Johnson
T. L. Page
J. S. Young
P. M. Daling

6. DATE REPORT ISSUED

MONTH	YEAR
December	1984

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

8. PROJECT/TASK/WORK UNIT NUMBER

9. FIN OR GRANT NUMBER
B2463-4

10. SPONSORING ORGANIZATION NAME AND MAILING ADDRESS (Include Zip Code)
Division of Radiation Programs and Earth Sciences
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

11a. TYPE OF REPORT

b. PERIOD COVERED (Inclusive dates)

12. SUPPLEMENTARY NOTES

13. ABSTRACT (200 words or less)

Fouling of raw-water systems in nuclear power plants in the United States can affect the safe operation of a power plant. This report describes correlations between the biology of bivalve organisms and the design and operation of power plants that allow bivalves to enter and reside in nuclear power plants. Discussions are focused on safety-related raw-water systems subject to fouling by the Asiatic clam (Corbicula fluminea), the blue mussel (Mytilus edulis), and the American oyster (Crassostrea virginica). Score sheets to rate fouling potential of power plant systems and components are provided.

14. DOCUMENT ANALYSIS – a. KEYWORDS/DESCRIPTORS
Biofouling, Asiatic clam, blue mussel, American oyster, nuclear power plant service-water system, circulating raw-water (CRW)

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

OFFICIAL BUSINESS
PENALTY FOR PRIVATE USE, $300

120555078877 1 1AN1RE
US NRC
ADM-DIV OF TIDC
POLICY & PUB MGT BR-PDR NUREG
W-501
WASHINGTON DC 20555