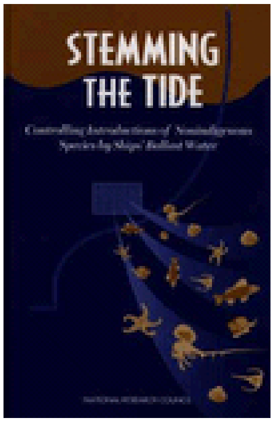

Stemming the Tide: Controlling Introductions of Nonindigenous Species by Ships' Ballast Water

Committee on Ships'Ballast Operations, National Research Council

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STEMMING THE TIDE

Controlling Introductions of Nonindigenous Species by Ships' Ballast Water

Committee on Ships' Ballast Operations
Marine Board
Commission on Engineering and Technical Systems
National Research Council

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This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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Preface

BACKGROUND

A great many nonindigenous species have been introduced into new environments in the United States and throughout the world as a result of human activity. Although many introduced species do not become established and do not have a major impact, many have detrimental effects on the ecosystem and human society, including the economy, recreation, and health.

Reports of marine and freshwater invasions of nonindigenous species have increased as human activity continues to disperse organisms at a significant rate. Species are transferred to new environments, intentionally or unintentionally, by many vectors, including ship hulls and anchors, where organisms may attach or become entangled; commercial products, whereby organisms are unknowingly transferred along with cargo (e.g., predators and diseases carried with commercial oysters); and the planned release of edible species for aquaculture. One important pathway is through ships' ballast water, which is necessary for safe ship operations and which may be taken on and discharged at the port of departure, during the voyage, and at the arrival port. This study addresses the effects and control of ballast water. Ballast is defined as any solid or liquid placed in a ship to increase the depth of submergence of the vessel in the water (the draft), to change the trim, to regulate the stability, or to maintain stress loads within acceptable limits. For the purposes of this study, the term ballast also includes sediment.

The negative economic and environmental impact of introducing nonindigenous species has been substantial. In an effort to address the problem, the U.S. Congress passed P.L. 101–646, The Nonindigenous Aquatic Nuisance Prevention and Control Act of 1990. Several of the provisions of the act directly address the challenges of ballast water as a vector for exotic species.

Also in 1990, the International Maritime Organization (IMO), which establishes standards for the maritime industry, published voluntary guidelines for controlling the discharge of ballast water. Because the uncontrolled discharge of ballast water is an international problem that can be expected to get worse, the IMO has established a working group to consider adding regulatory measures. In 1995 a member of the U.S. delegation succeeded an Australian delegate as chair of the IMO ballast water working group. The working group is furthering development of the guidelines and considering the formulation of a new annex to MARPOL 73/78[1] regarding control of ballast water.

Strategies for preventing the introduction of unwanted aquatic organisms through the discharge of ballast water and sediment include controlling when and where ballast water can be taken on or discharged and treating ballast water by a range of physical, chemical, mechanical, and biological processes. Related issues include whether new or different standards are needed, whether the voluntary regime should be made mandatory, whether the problem should be addressed on a regional or a worldwide basis, and the extent to which recordkeeping is needed. In conjunction with these issues, the questions of operational practicability, seafarer and ship safety, biological effectiveness, environmental impact, post-treatment monitoring and assessment, and cost-effectiveness of various options must be considered.

ORIGIN AND SCOPE OF THE STUDY

Legislation was introduced in the 103rd U.S. Congress that would have mandated a program to demonstrate technologies for treating ballast water and identify current management practices. The legislation (which did not come to fruition) included a feasibility study to be implemented by the National Research Council (NRC) that would identify the most promising technologies and management practices for demonstration. As a result of discussions with member agencies of the Aquatic Nuisance Species Task Force (mandated under P.L.101–646)[2] and congressional staff, the NRC convened a committee under the auspices of the Marine Board to undertake a focused study of technologies for preventing and controlling the introduction of nonindigenous marine species by ships' ballast operations.

The present study addresses the needs outlined in the proposed federal legislation calling for a feasibility study and demonstration program and assesses the

[1] The Protocol of 1978 relating to the International Convention for the Prevention of Pollution from Ships, 1973.

[2] The interagency Aquatic Nuisance Species Task Force is jointly chaired by the National Oceanic and Atmospheric Administration and the U.S. Fish and Wildlife Service. Other federal agencies with representatives on the task force are the Coast Guard, the Army Corps of Engineers, the Environmental Protection Agency, the Animal and Plant Health Inspection Service of the Department of Agriculture, and the Department of State.

state of practice of measures used to control aquatic nuisance species from ballast operations in the regional, national, and international arenas. All aquatic environments that are affected by ballast water operations, including the Great Lakes, are included in the scope of this study. The committee's tasks were:

- Assess the state of practice of preventing and controlling the introduction of nonindigenous species via ship operations, including voluntary guidelines at the regional, national, and international levels.
- Appraise potential alternative control strategies and management options for biological efficacy, practicability, and cost-effectiveness, as well as for their impact on ship and crew safety and the environment.
- Identify needs for research and technology demonstration, including the development of a framework for a demonstration project, if warranted.

Committee members were selected to include a broad spectrum of viewpoints at the regional, national, and international levels and to provide the wide range of expertise needed. Members represented the fields of biological oceanography, environmental biology, shipping, naval architecture, port operations, civil and sanitary engineering, and marine policy. Biographical information is presented in Appendix A.

The committee was assisted by liaison representatives from seven federal agencies with related programs or missions: the U.S. Department of Transportation-U.S. Coast Guard, the National Oceanic and Atmospheric Administration, the U.S. Fish and Wildlife Service, the U.S. Environmental Protection Agency, the U.S. Navy, the Department of Transportation-Maritime Administration, and the U.S. Department of State.

STUDY METHODS AND REPORT ORGANIZATION

The full committee met five times over a 16-month period. The committee reviewed relevant literature—including a number of overseas reports on managing ballast water—and was briefed on activities at the federal level related to aquatic nuisance species, notably the actions of the Aquatic Nuisance Species Task Force and the Risk Assessment and Management Committee. The committee also solicited information from researchers and practitioners in federal agencies, regional task groups, the shipping industry, and technology development organizations. In addition, the committee developed a questionnaire on candidate technologies for treating ballast water, which was sent to suppliers and developers of water treatment systems and research organizations (see Appendix G). These data-gathering activities were supplemented by visits to the ports of Long Beach and Los Angeles, California, where the committee was briefed on shipping practices while touring a tanker and a container vessel. The committee also visited the Port of Duluth to learn about control practices in the Great Lakes.

Committee members met several times in smaller groups to develop particular aspects of the report. The committee also held a two-part workshop in May and August 1995 to gather data on candidate technologies for treating ballast water. Information on committee meetings and other activities is given in Appendix B.

Chapter 1 of the report provides an overview of the role of ballast water in the dispersal of nonindigenous aquatic organisms. The use of ballast in ship operations is discussed in Chapter 2, which highlights the importance of ballast in ensuring ship safety. Chapter 3 addresses management of ballast water. Potential strategies for controlling ballast water are discussed in the context of ongoing activities by international, national, regional and other bodies; the chapter concludes with a brief discussion of the role of risk analysis in the development of options for managing ballast water. Chapters 4 and 5 comprise the technical core of the report. In these chapters, candidate technologies for shipboard treatment of ballast water are identified and evaluated based on criteria developed by the committee. The principal advantages and limitations of the most promising candidates are also discussed, with a view to developing for shipboard demonstration, and requirements for monitoring ballast water are discussed in the context of possible scenarios. Finally, opportunities for applying available and emerging monitoring techniques are identified. The committee's conclusions and recommendations are presented in Chapter 6.

ACKNOWLEDGMENTS

The committee wishes to thank the many individuals who contributed their time and effort to this project in the form of presentations at meetings, correspondence, or telephone calls. Special thanks are due to Mr. Jerry Aspland, Captain Jim Morgan, and the crew of the ARCO tanker, *Prudhoe Bay*; Captain Kim Davis, Captain Joseph Delehant, and the crew of the Sea Land containership, *The Patriot*; and the Port of Duluth for hosting committee visits. The hospitality of BHP Hawaii during the implementing change task group meeting is gratefully acknowledged.

The committee wishes to acknowledge the valuable contributions to the study made by its liaisons with project sponsors: Robert Blumberg, Office of Marine Law and Policy, Department of State; Leon Cammen, National Oceanic and Atmospheric Administration, National Sea Grant College Program; Lauren Kabler, Marine Environmental Protection Division, U.S. Coast Guard; Herbert Kirsch, National Oceanic and Atmospheric Administration, Office of Policy and Strategic Planning; Lawrence Koss, Office of the Chief of Naval Operations; Daniel Leubecker, Department of Transportation, Maritime Administration; Michael Slimack, U.S. Environmental Protection Agency; and Jay Troxel, U.S. Fish and Wildlife Service. The contribution made by Richard Seymour, the Marine Board liaison to the committee, is also gratefully acknowledged.

Finally, the chairman wishes to recognize the members of the committee for their hard work during meetings and reviewing drafts of the report and for their individual efforts in gathering information and writing sections of the report.

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INTRODUCTION OF NONINDIGENOUS SPECIES

Global shipping moves 80 percent of the world's commodities and is fundamental to world trade. Humans and ships have moved across the oceans for centuries; however trade routes and the vessels that sail them have changed and continue to change, as do port, estuarine, and ocean environments. This dynamic environment favors continued introductions of nonindigenous organisms—including mice, rats, cockroaches, water fleas, jellyfish, crabs, clams, fish, and snails—transported to new locations by ships. The potentially adverse effects of such introductions were illustrated by the discovery in the 1980s of the fouling European zebra mussel in the Great Lakes, a toxic Japanese dinoflagellate in Australia, and a carnivorous North American comb jellyfish in the Black Sea. These three introductions alone have cost many millions of dollars in remedial action; have had deep and broad ecological repercussions; and have focused government, public, and scientific attention on the role of shipping as a dispersal vector for nonindigenous aquatic organisms. Action to control unwanted introductions is being considered by individual nations and in the international arena under the auspices of the International Maritime Organization (IMO). In 1990, the U.S. Congress enacted P.L. 101-646 (the Nonindigenous Aquatic Nuisance Prevention and Control Act aimed at preventing future introductions of potentially harmful aquatic nonindigenous species and controlling existing unintentional introductions. The objective of developing strategies for managing ballast water is to reduce the likelihood of new introductions to an acceptable level without compromising ship safety.

Oceangoing ships disperse aquatic organisms through the uptake, transport, and subsequent discharge of water from ballast tanks. It has been estimated that more than 3,000 species of animals and plants are transported daily around the world in ballast water, which is required for safe operation under a range of conditions.[1] For the purposes of this study, the term ballast includes sediment, which is the debris suspended in ballast water as it is loaded that subsequently accumulates on horizontal surfaces in ballast tanks. Ship owners since time immemorial have endeavored to avoid using ballast, preferring to carry revenue-earning cargo. Nevertheless, ballast is always necessary for the successful and safe operation of ships.

Any approach to managing ballast water and controlling introductions of nonindigenous aquatic species must take into account that there may be several source regions and release sites of ballast water on any sea voyage. The biota in ballast water are correspondingly diverse, and predicting the presence of a particular unwanted species in a particular vessel or certifying a particular vessel as free of or safe from all unwanted species is extremely difficult. The diversity of potential introductions and the numerous environmental factors (e.g., water temperature, nutrient levels, and the extent and nature of pollution) determining the fate of organisms discharged with ballast water make it impossible to predict what the next introduction will be or when and where it will occur. Nevertheless, it can be stated with confidence that further introductions will take place and that ballast water is an important vector contributing to the dispersal of nonindigenous aquatic organisms.

POTENTIAL CONTROL STRATEGIES

Changing ballast at sea is currently the favored technique for reducing the risk of introducing nonindigenous aquatic organisms into the marine environment through discharged ballast water. Ballast water loaded in port or taken on board while transiting inshore waters is charged with ocean water during passage between ports of call. This method is usually effective because most freshwater estuarine, and inshore coastal organisms cannot survive when discharged into the ocean environment. Similarly, freshwater, estuarine, or inshore coastal waters are inhospitable to oceanic organisms. One of the main functions of ballast is to ensure the stability and manageability to ships at sea. Therefore, altering the ballast condition while under way may jeopardize vessel safety. In addition, the design of most ballast systems does not permit the removal of all ballast and associated biota. Thus, while changing ballast may be an acceptable and effective control method under certain circumstances, it is neither universally applicable nor totally effective, and alternative strategies are needed.

[1] Ballast water is generally used in preference to solid ballast because of reduced loading times and increased vessel stability during a voyage.

The committee categorized the range of potential strategies for controlling ballast water as follows:

- On or before departure. Control is based on preventing or minimizing the intake of organisms when ballast water is loaded at the port of origin.
- En route. Control is based on the removal of viable organisms by shipboard treatment or ballast change prior to the discharge of ballast water at the destination port.
- On arrival. Control depends on preventing the discharge of unwanted organisms that could potentially survive in the new environment.

The viability of different control options depends not only upon their biological effectiveness but also on vessel size and type and the loading and discharge capacities of ballast pumping and piping systems. Given this diversity of vessels and the complexity of ballasting patterns, the committee determined that flexibility in managing ballast water is essential for adequate protection against introductions of unwanted nonindigenous aquatic organisms.

Biological scientists cannot currently state what level of ballast water control is effective, and existing guidelines for controlling introductions of nonindigenous aquatic nuisance species do not identify an acceptable level of risk. Risk-based approaches to managing ballast water, using quantitative risk assessment methodology, are being investigated in the United States and Australia.

There is currently no universally applicable option for controlling ballast water that can totally prevent the unintentional introduction of nonindigenous aquatic nuisance species. The use of available control methods is limited by requirements for safety, environmental acceptability, technical feasibility, practicability, and cost effectiveness. Nonetheless, there are a number of control options that could be undertaken today that would immediately reduce the transport of nonindigenous species by ballast water. These options include avoiding ballasting if water is likely to contain unwanted organisms (for example, in areas of sewage discharge or high sediment loads). A plan for managing ballast water developed in conjunction with the ship cargo plan would provide flexibility for meeting contingencies and avoiding ballasting in certain locations.

Both shipboard and shore-based facilities for treating ballast water merit further investigation. The concept of shore-based reception facilities for oily ballast has gained acceptance, although such facilities are not widely used. Shore-based treatment of ballast water may have some advantages, but there is no precedent in the United States for recovering associated infrastructure costs, and shipboard treatment is more likely to be implemented.

In the absence of a universally applicable method of managing ballast water, the committee identified a need for additional research and development to improve methods of killing or removing organisms in ballast water. In the view of the committee, international coordination of research on ballast water would both stimulate activity and avoid duplication of effort.

SHIPBOARD TREATMENT OPTIONS

Shipboard treatment provides the most flexibility in managing ballast water. The committee identified 10 major categories of candidate shipboard treatment technologies: biocides (oxidizing and nonoxidizing), filtration, thermal treatment, electric pulse/pulse plasma treatment,[2] ultraviolet, acoustics, magnetic, deoxygenation, biological, an anti-fouling coatings. A number of these technologies are used extensively in waste-water treatment. However, the requirements for the shipboard treatment of ballast water are somewhat different. The space and power available on board ship are limited, and very large volumes of ballast water must be treated without compromising the safety of the ship or crew.

As a basis for gathering information on candidate systems, the committee developed a questionnaire about the options for treating ballast water. Two representative scenarios of ballasting requiring treatment were defined:

System A. Flow rate of 2,000 m^3/h and tank volumes of up to 25,000 m^3, with residence times as short as 24 hours.
System B. Flow rate of 20,000 m^3/h and tank volumes of up to 25,000 m^3, with residence times as short as 24 hours.

Data were sought on a range of system characteristics, including equipment and space requirements; capital and operating costs; safety; effectiveness in destroying or removing a range of aquatic organisms; byproducts of treatment; operation, training, and manpower requirements; and performance over a range of temperatures and salinities in the presence of sediment. Responses to the questionnaire were received from equipment suppliers, technology developers, and research organizations. Additional information on candidate treatment technologies was obtained from product literature and articles in scientific and technical journals.

The committee identified a series of parameters for rating technologies for potential application in shipboard treatment of ballast water. Safety is critical in evaluating strategies for managing ballast water. In addition, strategies are only worthwhile if they effectively reduce the number of viable organisms in ballast water. Therefore, safety and effectiveness were used as the first gate in evaluating candidate systems. Four technologies were judged by the committee to meet requirements for safety and effectiveness: biocides, filtration (media and film), thermal, and electric pulse/pulse plasma. Biological treatment and antifouling coatings were not evaluated in any detail. The other candidate systems were deemed safe but did not meet the criterion for effectiveness in treating the wide range of organisms found in ballast water.

[2] For the purposes of the present technology evaluation, electric pulse and pulse plasma treatments were addressed together. In both cases, organisms are inactivated by the application of an energy pulse.

The committee evaluated the technologies that met the safety and effectiveness criteria in terms of other important criteria for shipboard use, namely:

- commercial availability of proven systems, including marine systems
- power requirements
- production of chemical residuals during treatment
- possibility of increasing effectiveness by recirculating ballast water
- cost, both capital and operating (including possible impact on crew size)
- size and complexity
- ease of maintenance
- ease of monitoring performance

Although no single technology received good ratings in all categories, the committee identified several promising candidates. The most promising technologies for the successful shipboard treatment of ballast water are physical separation methods, particularly constant backwash fine screening. Adding low concentrations of biocides to kill unwanted organisms is also a promising option. Thermal treatment may be practical for certain vessels on specific trade routes. Other technologies require significant development before they can be considered suitable for shipboard treatment of ballast water. The absence of an off-the-shelf treatment technology suitable for use on board ship further highlights the need to consider diverse approaches to managing ballast water.

MONITORING

Monitoring ballast water has two major purposes in the context of current efforts to control introductions of nonindigenous aquatic nuisance species. First, monitoring (supported by appropriate record keeping) is needed to audit methods of controlling ballast water for compliance with regulations or guidelines; therefore, monitoring is an integral part of the process for managing ballast water. Second, monitoring is a research and development tool for assessing the effectiveness of ballast water treatments, increasing understanding of the nonindigenous species problem, and developing plans for managing ballast water. Thus, the committee identified monitoring as a very important component of both current and future efforts to control introductions by ships' ballast water.

Shipboard monitoring systems need to be safe, inexpensive, rugged, compact, easy to use, and quick to operate—even for personnel with little training. Onboard monitoring imposes more constraints and requirements than land-based monitoring. Because implementing measures for managing ballast water will require practical measures for verification, accountability, and responsibility, automated monitoring methods are desirable.

The monitoring needed in any given situation will be closely linked to approaches adopted for managing ballast water. In general, the monitoring effort and associated costs will decrease as the effectiveness and cost of strategies for managing ballast water increase. The trade-off between levels of treatment and monitoring must be taken into account in assessing the cost effectiveness of strategies for managing ballast water.

The committee identified three levels of monitoring that might be needed for vessels that have either changed ballast at sea or have taken no action to control potential nuisance organisms in ballast. Vessels that have undertaken shipboard treatment of ballast water represent a somewhat different situation because monitoring requirements will generally be determined by the treatment method. The three proposed levels are as follows:

- Level I. Log of change events and basic water quality parameter description
- Level II. Basic bioactivity and indicator species description
- Level III. Advanced biological analysis

Level I monitoring is the simplest and least expensive; level III is the most complex and expensive and is not likely to be practicable with existing technology. The committee anticipates that monitoring will be conducted at the lowest level necessary for determining with confidence that the discharge of ballast water does not pose an unacceptable risk of introducing nonindigenous aquatic species.

The committee believes that level I monitoring could be readily implemented and that it would be effective for ships that change ballast at sea. The basic parameters indicative of water quality—turbidity, salinity, temperature, dissolved oxygen content, and pH—can be readily measured using commercial instruments and test kits suitable for marine applications. In addition, records of ballast water operations are already kept by the vast majority of vessels. Examination of these records, in conjunction with testing of basic water quality parameters to confirm ballast movements, would generally provide adequate assurance that the ballast tanks contain oceanic rather than estuarine water. Thus, mandatory maintenance of ships' logs and records with data on all ballast-water movements for verification by shore officials would assist in implementing control measures and would reduce the need for detailed monitoring in many instances.

Vessels that have not treated or changed ballast water at sea are unlikely to be able to rely on level I monitoring approaches and will require level II or level III analyses.[3] The presence of life in ballast water (level II monitoring) can easily be determined in a laboratory environment by assessing levels of bioactivity based on measurements of photosynthetic pigment, adenosine triphosphate, nucleic acids, and nutrients. Advanced biological analysis (level III monitoring) requires the taxonomic identification of organisms, possibly to species level; is time consuming and expensive; and cannot currently be performed on board ship. It may be possible to develop inexpensive biomonitoring techniques for ballast water that are amenable to shipboard use.

[3] Exceptions may occur when vessels are transiting climatic extremes; for example, when they ballast in polar waters and deballast in tropical waters.

Monitoring ships' ballast is complicated by the need to analyze not only the water column but also the sediment that accumulates at the bottom of tanks and holds. Periodic monitoring of sediment is necessary because sediment may be a source of transported organisms.

Under certain circumstances onboard monitoring systems are not practical or are too expensive to install. A system of ballast water sampling and dispatch has been suggested as an alternative to shipboard monitoring. Developing this approach for a range of organisms represents a major challenge in terms of both sampling and testing. It is also not clear if potentially harmful species can be identified as such prior to their introduction. However, baseline sampling of ports for the presence of specific organisms to standardized, internationally accepted criteria would be helpful in determining the risk associated with voyages between specified ports. Port baseline surveys represent a significant scientific undertaking and would require periodic updating.

REGULATIONS AND GUIDELINES

The U.S. Coast Guard regulations for controlling nonindigenous species in ballast water in the Great Lakes, which were promulgated in response to P.L. 101-646, are the only mandatory regulations for managing ballast water in effect in the United States. The regulations apply to vessels that have operated outside the exclusive economic zone of either the United States or Canada. Overseas, Chile and the port of Haifa in Israel have introduced requirements making it mandatory that ballast water be changed prior to being discharged.

In addition to these mandatory requirements, there are a number of international, national, regional, state, and local initiatives to control introductions of nonindigenous aquatic nuisance species. In particular, the IMO has developed guidelines for preventing the introduction of unwanted aquatic organisms from discharged ballast water and sediment, and IMO member states have been requested to apply these guidelines on a voluntary basis. The Marine Environment Protection Committee of IMO is currently drafting a set of regulations for a possible new annex to MARPOL 73/78[4] that would make use of the guidelines mandatory. If acceptable to IMO's contracting nations, the new annex could be ratified around the turn of the century. The guidelines can be continuously updated, incorporating the results of research and development and improved technologies, without changing the regulations of the annex.

In an international context, the committee concluded that regulations to control introductions would be most effective in the form of an amendment to an existing international convention or treaty. The introduction of unilateral legislation and regulations by individual nations would result in a complicated "patchwork" of

[4] The Protocol of 1978 relating to the International Convention for the Prevention of Pollution from Ships, 1973.

national requirements, which operators of vessels in international trade would find difficult to understand and comply with. The committee proposes that, in the interest of simplifying compliance, the United States develop domestic guidelines for managing ballast water that mirror the IMO voluntary guidelines. The implementation of national guidelines would be facilitated by a targeted education program for those directly involved in managing ballast water.

Regional initiatives include those in the Great Lakes and Chesapeake Bay. A notable feature of these regional initiatives is the involvement of a broad group of participants, including the representatives of the shipping industry, ports, the scientific community, and regional, state, and federal governments. Cooperation at the regional level goes beyond legal mandates. The committee judged this kind of cooperation to be an important factor in addressing the problem of nonindigenous species transfer, which is not simply an issue for the shipping industry but has implications for society as a whole.

The committee identified measures that could be taken now—in parallel with research and development and demonstration programs—to facilitate managing ballast water. The mandatory maintenance of logs recording all ballast water movements was addressed above. The committee also anticipates that onboard monitoring of basic water quality parameters could be implemented in the near future. In addition, the committee determined that the development of a plan to manage ballast water, in conjunction with the cargo plan, would provide flexibility in loading and discharging ballast water. The plan should be mandatory when the ports of call include one or more known sources of unwanted organisms.

RECOMMENDATIONS

On the basis of its review, the committee recommends the following:

Recommendation for the U.S. Coast Guard. Managing the unintentional introduction of nonindigenous organisms into U.S. waters through ballast water should follow two parallel courses:

- Support current international activities conducted under the auspices of IMO.
- Introduce national voluntary guidelines to minimize the risk of introductions until such time as mandatory international standards can be developed. These guidelines should require a plan for ballast water loading and discharge, developed in conjunction with the cargo plan for each voyage.

Recommendation for the Aquatic Nuisance Species Task Force. The following actions should be taken as part of the cooperative national program to prevent unintentional introductions of nonindigenous organisms through ballast water:

- The United States should support and encourage the early elaboration of a new annex to MARPOL 73/78 making the existing voluntary guidelines mandatory; meanwhile, the IMO-sponsored voluntary guidelines should be continuously reviewed and updated.

- The cognizant U.S. authority,[5] as a matter of priority, should be tasked with developing domestic guidelines to minimize the translocation of unwanted nonindigenous organisms among U.S. ports by vessels engaged in trade along U.S. coasts. All interested parties should be involved from an early stage in formulating guidelines and in developing ways to implement them.
- The associated U.S. authorities should sponsor and encourage further research and development for killing or removing aquatic organisms in ballast water. In this regard, options for treating ballast water should not be limited to technologies for shipboard use. Shoreside treatment should be investigated as a possible alternative.

Recommendation for the Aquatic Nuisance Species Task Force. National research and development, including one or more demonstration projects, should focus on the following:

- optimizing the filtration approach to treating ballast water
- identifying the level of biological activity that indicates that treatment has reduced the risk of species introduction to an acceptable level
- developing automated monitoring systems suitable for shipboard use

To avoid duplication of effort, these activities should take into account related research and development in other countries.

Recommendation to the Aquatic Nuisance Species Task Force. The results of this study should be disseminated to coastal states, including states bordering the Great Lakes.

Recommendation for the U.S. maritime industry. At the same time research and development are undertaken to address long-term solutions for controlling introductions of nonindigenous aquatic organisms, the U.S. maritime industry should pursue implementation of a combination of practices for managing ballast water and the control options described herein, within the framework of existing international guidelines.

Recommendation for the member states of IMO. Future international considerations should include establishing guidelines for baseline sampling of ports for specific organisms. Samples should be tested to agreed-upon international standards to facilitate comparisons of the water of each ballast uptake port with the water of receiving ports.

[5] The cognizant U.S. authority may be the Coast Guard, the state, or the port authority, depending on circumstances.

Recommendation for the member states of IMO. In future discussions and updates of the existing voluntary guidelines (IMO Assembly Resolution A.774(18), 1993), consideration should be given to the maintenance of appropriate logs and records of ballast water movements and any management practices used. These data could be valuable when used in conjunction with basic water-quality measurements to verify that ballast water has been effectively managed.

1

Ballast Water and Nonindigenous Species

The discovery in the 1980s of the fouling European zebra mussel in the Great Lakes, of a toxic Japanese dinoflagellate in Australia, and a carnivorous North American comb jellyfish in the Black Sea—all of whose successful establishments led to critical economic, human health, and ecological concerns—focused scientific, governmental, and public attention on an age-old phenomenon: the introduction of nonindigenous organisms transported to new locations by ships. There are many dispersal vectors for the transport or organisms on board ships. The most important of these appears to be water in ships' ballast[1] tanks and in cargo/ballast holds (Carlton, 1985; Williams et al., 1988; Carlton and Geller, 1993). It has been estimated that in the 1990s ballast water may transport over 3,000 species of animals and plants a day around the world (NRC, 1995), and there is evidence that the number of ballast-mediated introductions is steadily growing. More than 40 species have appeared in the Great Lakes since 1960; more than 50 have appeared in San Francisco Bay since 1970 (see Figure 1-1).

Ballast water and sediment frequently contain abundant living organisms reflecting in large part whatever is in the water around and under the ship at the time of ballasting. In turn, ballast water released from ships acts as an inoculation mechanism for nonindigenous species. Nonindigenous species—also known as exotic species, alien species, and biological invasions—are defined in this report as any species or other viable biological material that enters an ecosystem beyond

[1] Ballast is defined as any solid or liquid placed in a ship to increase the draft, to change the trim, to regulate the stability, or to maintain stress loads within acceptable limits. For the purposes of this study, the term ballast includes the sediment that accumulates in ballast tanks, which may be discharged with ballast water (see Chapter 2).

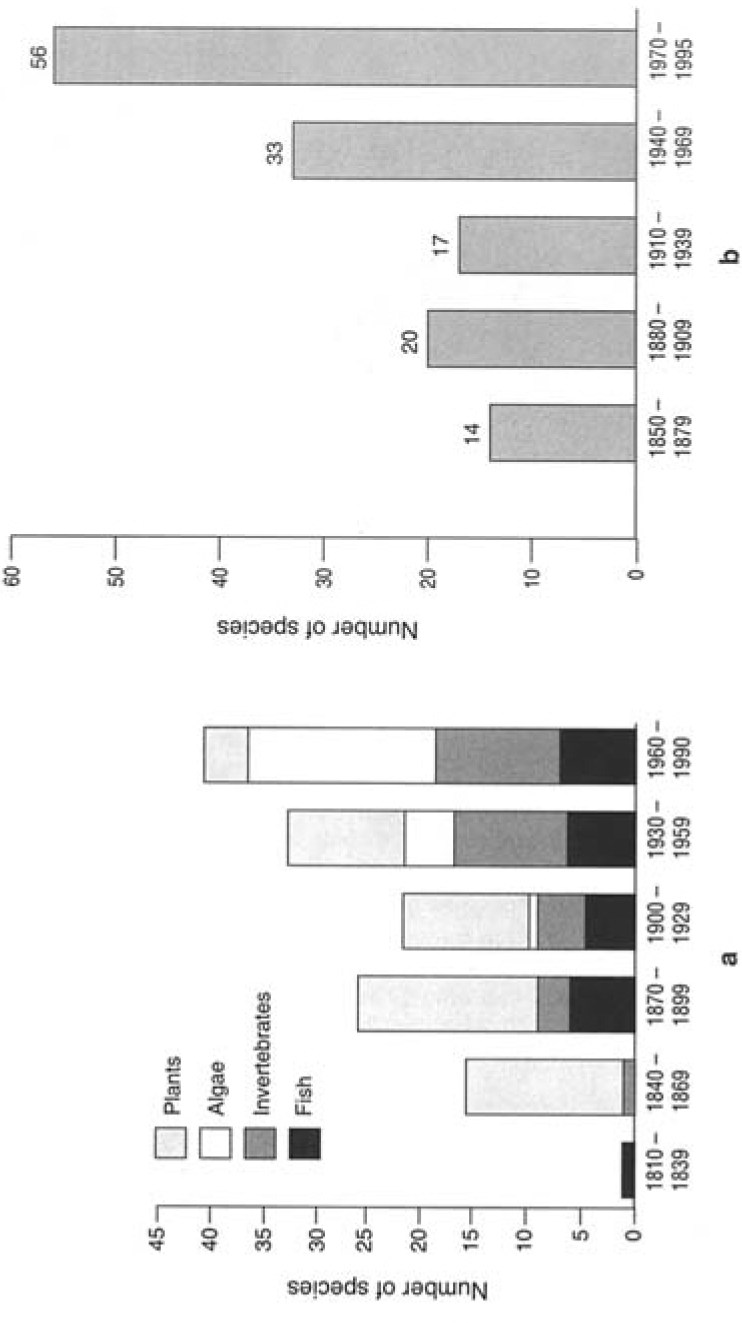

FIGURE 1-1 Introductions of nonindigenous aquatic plants and animals in (a) the Great Lakes and (b) the San Francisco Bay region. Note: Introductions shown as the date of first collection of newly discovered exotic species. Sources: Mills et al., 1993; Cohen and Carlton, 1995.

its historic range, including any such organism transferred from one country into another (P.L. 101-646, 1990). Tables 1-1 and 1-2 provide examples of shipborne introductions.[2]

TABLE 1-1 Examples of Shipborne Introductions Worldwide since the 1980s

Species	Origin	Location
Dinoflagellates		
Gymnodinium catenatum	Japan	Australia
Comb Jellyfish (Ctenophora)		
Mnemiopsis leidyi	North America	Black and Azov Seas
American Comb Jellyfish		
Polychaete Worms (Annelida)		
Marenzelleria viridis	North America	Western and Northern Europe
Spionid Tubeworm		
Mussels and Clams (Bivalvia)		
Ensis americanus	North America	Western and Northern Europe
American Razor Clam		
Musculista senhousia	Japan	New Zealand
Japanese Mussel		
Crabs (Decapoda)		
Charybdis helleri	Mediterranean	Colombia, Venezuela, Cuba, and United States
Indo-Pacific Swimming Crab		
Seastars (Asteroidea)		
Asterias amurensis	Japan	Australia
North Pacific Seastar		

Sources: Carlton and Geller, 1993; Carlton et al., 1995; LeMaitre, 1995.

Humans and ships have moved across the oceans for centuries; however, trade routes and the vessels that sail on them have changed and continue to change, as have the environments that donate and receive nonindigenous species. Because the mechanisms that transport organisms from one region to another and to the ocean are dynamic systems and are everchanging, nonindigenous species continue to be introduced (Carlton, 1996). Such introductions may have critical economic, industrial, human health, and ecological consequences. Thus, there are compelling arguments for reducing the role of ships as a vector of nonindigenous species, particularly through ballast water. For example, the three introductions noted above (i.e., zebra mussel, dinoflagellates, and comb jellyfish) have cost tens of millions of dollars and have had deep and broad ecological repercussions (Hallegraeff, 1993; Nalepa and Schloesser, 1993; Harbison and Volovik, 1994).

[2] Maps indicating locations where nonindigenous aquatic nuisance species have been found are provided in a number of articles (see, for example, Jones, 1991).

TABLE 1-2 Examples of Shipborne Introductions in the United States since the 1970s

Species	Origin	Location
Jellyfish (Hydromedusae)		
Maeotias inexspectata	Black Sea	Chesapeake Bay
Black Sea Jellyfish		San Francisco Bay
Blackfordia virginica	Black Sea	Chesapeake Bay
Black Sea Jellyfish		San Francisco Bay
Water Fleas (Cladocera)		
Bythotrephes cederstroemi	Europe	Northeastern North America
Spiny water flea		
Copepods (Copepoda)		
Limnoithona sinensis	China	San Francisco Bay
Oithona davisae	Japan	San Francisco Bay
Sinocalanus doerrii	China	San Francisco Bay
Pseudodiaptomus marinus	Japan	San Francisco Bay
Pseudodiaptomus inopinus	Asia	Columbia River
Pseudodiaptomus forbesi	China	San Francisco Bay
Crabs (Decapoda)		
Hemigrapsus sanguineus	Japan	Massachusetts to Virginia
Japanese shore crab		
Mussels, Clams, and Snails (Mollusca)		
Dreissena polymorpha	Eurasa	Eastern North America
Zebra Mussel		
Dreissena bugensis	Eurasia	Eastern North America
Quagga Mussel		
Perna perna	South America	Gulf of Mexico
South American Mussel		
Potamocorbula amurensis	China, Japan	San Francisco Bay
Asian clam		
Philine auriformis	New Zealand	California
New Zealand Seaslug		
Moss Animals (Bryozoa)		
Membranipora membranacea	Europe	Gulf of Maine to New York
Kelp bryozoan		
Fish (Osteichtyes)		
Neogobius melanostamus	Eurasia	Great Lakes
Round goby		
Preteorhinus Marmoratus	Eurasia	Great Lakes
Tubenose goby		
Gymnocephalus cernuus	Europe	Great Lakes
Ruffe		
Mugiligobius parvus	Philippines	Hawaii
Philippine Goby		

Source: Carlton, 1985; Carlton et al., 1990, 1995; Gosliner, 1995; Mills et al., 1993; Mills and Sommer, 1995; Randall et al., 1993.

DIVERSITY OF BALLAST WATER BIOTA

Virtually all ballast water samples taken to date in Canadian, Australian, German, and U.S. studies contained living macro-organisms, indicating that ballast water, including sediment, is a viable habitat for a wide variety of freshwater, brackish water, and saltwater organisms (Bio-Environmental Services, Inc., 1981; Jones, 1991; Hallegraeff and Bolch, 1992; Carlton and Geller, 1993). The potential diversity of biota in ballast is vast; virtually all organisms less than 1 cm in size that are adjacent to the vessel—naturally swimming in the water, stirred up from bottom sediment, or rubbed off harbor pilings—could be ballasted into a vessel. These include viruses, bacteria, protists (including protozoans), fungi and molds, and plants and animals. It is important to note that the parasites and symbionts of all of these organisms will, of course, also be transported.

The maximum size range of organisms that can be taken into a ship depends upon the method of ballasting and the size of the intake screens. Pumped water passes organisms through pump impellers, which may kill some organisms. If gravity-loading is used, organisms are not passed through an operating pump, thus eluding possible mechanical destruction, although there are still external and internal screens through which larger organisms generally cannot pass. However, exceptions may occur in poorly maintained vessels, allowing these larger organisms to be transported.[3]

Among the plants transported, phytoplankton, especially diatoms and dinoflagellates, have been found to be particularly common in ballast water (Carlton and Geller, 1993; Hallegraeff, 1993). The potential is high for the transport of floating, detached plants, including seaweeds (algae) and seagrasses (such as the eelgrass, *Zostera*, and the turtle grass, *Thalassia*). It has been suggested that the recent invasion of the Asian brown kelp, *Undaria pinnatifida*, in Australia may be related to ballast water release (Sanderson, 1990).

Among the animals, zooplankton can be both diverse and dense in ballast water. These include those planktonic organisms that spend most or all of their life cycle in the water, such as many types of protozoans, rotifers, copepods, opossum shrimp (mysids), arrow worms (chaetognaths), and fish. Zooplankton also include those planktonic animals that spend only a portion of their lives in the water column (meroplankton), in particular the larvae of many benthic invertebrates, including sea anemones, corals, hydroids, mollusks (snails, mussels, clams, oysters, and scallops), crustaceans (barnacles, shrimp, lobsters, crabs, hermit crabs), polychaete worms, echinoderms (seastars, brittle stars, sea urchins, sea cucumbers), tunicates (sea squirts), and the larvae of fish.

[3] A vessel from the Eastern Mediterranean arriving in Baltimore harbor in April 1995 was found to contain over 50 actively swimming individuals of a fish (*Liza*, a mullet) ranging from 30 to 36 cm (12 to 14 in.) in length in a ballasted cargo hold (Ruiz and Carlton, 1995). The grates or screens over the ballast sea chest may have fallen off allowing the intake of unusually large species.

The biota of the sediment in ballasted cargo holds of arriving ships are not well known. Williams et al. (1988) reported that vessels arriving in Australia contained diverse and abundant invertebrates that could be released if and when the sediment is discharged. Hallegraeff and Bolch (1992) further reported that ballast sediment may contain numerous dinoflagellate cysts. The biota of the sediment in ballast tanks are also not well known. The committee directly observed benthic communities established on the bottom of a dedicated ballast tank on a coastal trade vessel that, when deballasted, held unpumpable ballast to a depth of 15 to 30 cm (see Appendix B). A permanently submerged assemblage of polychaete worms, amphipods, shrimp, hydroids, nematodes, and other species had become established. These organisms could release planktonic larvae into the overlying ballast water, which could subsequently be discharged, and the resident adult community would remain on the bottom of the tank.

FATE OF DISCHARGED ORGANISMS

The release of nonindigenous species into a novel environment constitutes their inoculation but not necessarily their successful introduction. Inoculation is followed by differential survival; a long-standing observation is that most individuals disappear after release and do not form established populations (Carlton et al., 1995). It is not known how long most inoculated individuals simply survive. Older, isolated individuals of nonindigenous species that do not form reproducing populations are occasionally found, which indicates that a certain number grow to adulthood (Carlton, 1995).

As is true of all transport vectors (natural and synanthropic) and of all quarantine concerns, the greater the difference in the physical and chemical states of the donor (source) and receiver (target) regions, the lesser the probability of survival. Thus many organisms from tropical ports will not survive or reproduce in cooler, temperate or boreal ports, and vice-versa.[4] However, some species of marine invertebrates and algae occur from subpolar to tropical waters. Thus, the transport of organisms from a warm-water port to a cold-water port, or vice versa, cannot be classified as a "zero risk" scenario. Further, it is impossible to make a complete list of all potential unwanted introductions from a foreign source because many species do not manifest nuisance characteristics within their native ranges. Biological science cannot predict whether a species that is harmful at its source will present a risk when introduced to a new location. Thus, it is not possible to identify areas of zero risk where ballast controls are unnecessary.

Regardless of the match or mismatch in any one physical or chemical variable between a source environment and a release site for a species, numerous

[4] Exceptions occur when tropical and subtropical species are transported to and establish reproducing populations in power-plant thermal effluents, a phenomenon well known in Europe and North America.

other considerations come into play when determining whether a given species will become established (see also Box 3-3). Thus, even when temperatures of discharged ballast water and receiving waters are identical, factors such as salinity, oxygen, light, food resources, competitors, predators, substrate availability, and many others may be inhospitable or limiting.[5] These biological and ecological factors frequently vary dramatically over seasons and years, with the result that a species that is not successful at one time may later become established (Carlton, 1996).

COMPLEXITY OF BALLASTING PATTERNS

A critical concept in managing ballast water is that the source regions and release sites of ballast water frequently occur in a complex fashion along the vessel's route. The following hypothetical scenario is an example of how a vessel may have ballast water from multiple sources, with different water in different tanks or mixed in the same tank.

A vessel off-loads its cargo in a discharge port, having arrived with some ballast on board from a prior harbor (site 1). After completing cargo discharge, the vessel ballasts (site 2) in preparation for its transoceanic crossing to pick up cargo for another port. During passage additional water is loaded into storm ballast and cargo/ballast holds because of rough sea conditions (site 3). Some days later, due to fuel and freshwater consumption, more ballast is added mid-ocean for additional stability (site 4). Finally, additional ballast is taken aboard for clearance under a harbor bridge in the arrival port (site 5).

The result of this hypothetical scenario translates biologically into the vessel accumulating organisms from multiple ballastings at several sites. Thus, organisms arriving in ballast water are not necessarily strictly estuarine or coastal in origin, nor do all of them necessarily represent the last port of call. Ballast water may be hours to months old and may contain living organisms for an extended period of time. As noted above, sediment in ballast tanks may reflect an even longer history of ballasting and may include an accumulation of life forms from many ports around the world that have survived in the shipboard environment.

The movement and release patterns of ballast water are such that no coastal site, whether it receives direct shipping or not, is immune to ballast-mediated introductions. It is frequently assumed that only major port systems are at risk from introductions of organisms. However, ships may release ballast water as they pass along coastlines, often sufficiently close to shore that natural onshore advection may carry ballast-discharged organisms into small lagoons, bays, or any other coastal location. Coastal vessel traffic and coastal currents may also disperse introduced species from larger port systems to remote sites all along a coast.

[5] The committee notes that even apparent mismatches in the conditions listed may have exceptions. For example, many euryhaline species are known to survive in waters with salinity levels between 0 and 30 ppt.

IMPLICATIONS FOR MANAGING BALLAST WATER

The overall diversity of biota found in ballast and the complexity of ballasting patterns and operations mean that predicting the presence of a particular unwanted species in any one vessel is a scientific challenge. Similarly, the great diversity of the larval or juvenile stages of marine invertebrates and fish in ballast water, many of which are not identifiable, means that certifying a vessel as free or safe from all unwanted species is not possible. A further complication is that many of the most prominent introductions of recent years were not recognized as problem species in their donor regions. Thus the Asian clam, *Potamocorbula amurensis*, which has led to fundamental changes in the energy flow and dynamics of the San Francisco Bay estuary since its appearance in 1986 (Carlton et al., 1990; Alpine and Cloern, 1992), was not signalled as a species of concern in Western Pacific estuaries, nor would its larvae have been identifiable if ballast sampling programs had been in place in California prior to 1986.

In terms of managing ballast water, the multiplicity of factors influencing the establishment of nonindigenous organisms means that species (particularly those from comparable environments) found in ballast water samples that have not previously or subsequently been found in the receiving port cannot be assumed to be safe species that could be put on a "clean" list. Possible explanations have been postulated for the observation that a species may eventually become extraordinarily successful in waters where it may have been inoculated for many decades. The zebra mussel, *Dreissena*, in the North American Great Lakes (Carlton, 1996) is one example. Important factors include changes in the donor region, new donor regions, changes in the recipient region —including improved water quality—the opening of introduction windows (the proper combination of environmental conditions), stochastic inoculation events, and changes in the dispersal vector. As long as there are transport mechanisms, such as ballast water, there may be new introductions.

The objective of developing strategies for managing ballast water is to reduce the likelihood of new invasions to an acceptable level without in any way compromising ship safety. This requirement is complicate by the diversity of potential invaders and by the many environmental factors—often overlapping and synergistic—determining the fate of organisms discharged with ballast water.

OTHER DISPERSAL VECTORS

A ship is a biological island (see Box 1-1). Besides the potential complement of synanthropic hitchhikers (e.g., mice, rats, flies, and cockroaches) and the rich bouillabaisse of ballast water and sediment, living marine and estuarine organisms can occur elsewhere in and on the vessel. In this regard, it is necessary to distinguish the unique role of ballast water an sediment in transporting non-indigenous species from other ways in which a vessel may transport organisms.

BOX 1-1
LIFE BEYOND BALLAST

The modern ship transports living organisms on the hull, in sea chests, and elsewhere on and in the vessel, such as in seawater piping systems, on the rudder, entangled in the anchor or in the anchor chain, in chain lockers or caught up in fish nets. Ballast water has a clearly identified role in directly and consistently releasing large numbers of organisms in every major port of the world every day. This report focuses on ballast water as the major vector for the dispersal of nonindigenous aquatic organisms.

Of particular concern are organisms carried on the ship's hull and in sea chests (also known as sea boxes or suction bays). Despite numerous modern studies on the diversity of organisms transported in ballast water, relatively little is known about the diversity of marine life transported on hulls or in sea chests. In a number of cases there is obvious taxonomic overlap. For example, barnacles occur commonly both as adults on ships' hulls and as larvae in ships' ballast water. Should a new barnacle invasion occur, it would be difficult to determine which of these two vectors was responsible.

In the case of sea chests, the extent of potential overlap is much less clear. Thus, although starfish (seastars) are not likely to survive long sea voyages on the exposed hull of a vessel and seastar larvae occur in ballast water, sea chests may also conceivably support seastar populations. Sea chests, because of their protected nature, may harbor relatively larger accumulations of organisms—including mobile species such as snails that would normally be washed away from the ship's hull—than the outside of the ship. Carlton et al. (1995) suggested that the modern sea chest may be an analogue of the deep and protected shipworm galleries off wooden sailing ships. However, the committee is not aware of any modern scientific studies of sea chest fouling.

The general perception is that, because of anti-fouling paints, modern vessels typically do not develop the massive fouling communities that were the bane of mariners a century and more ago. However, the role of ships' fouling in transporting nonindigenous species remains unclear. Increased modern vessel speeds, decreased port time, and increased vessel performance (to offset vessel operating costs) suggest that the number of marine organisms transported in fouling communities may have decreased over time. Conversely, the role of ship fouling may have increased for some species and for some trade routes for a number of reasons, including the evolution of strains of certain seaweeds resistant to anti-fouling paint; the greater sea-going speeds of modern vessels, which lead to decrease in transport times and a resultant increase in survival rates of oligohaline organisms; and the decreased use globally of certain types of anti-fouling paints, such as those containing tributyltins (Hall, 1981; Weis and Cole, 1989; Carlton et al., 1995). The net result of these negative and positive influences on the diversity of fouling communities is not known.

Temporal considerations further hinder predictions of the relative roles of ballast versus other ship-mediated vectors. Fouling communities are transported to a "new" port with every visit of every ship; significant amounts of ballast water are released only by those vessels loading cargo, and different ports receive significantly different amounts of ballast water. On the other hand, for fouling communities to act as effective vectors of non-native species, the organisms involved must either reproduce in the short time a vessel is in port or must be dislodged and fall of the ship. The latter situation is less likely for organisms residing in the protected sea chest.

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2

Ballast Water and Ships

Ships have always required ballast to operate successfully and safely. For millennia, ships carried solid ballast in the form of rocks, sand, roof tiles, and many other heavy materials. From the 1880s onward, ships increasingly used water for ballast, thereby avoiding time-consuming loading of solid materials and dangerous vessel instabilities resulting from the shifting of solid ballast during a voyage. Today, vessels carry ballast that may be fresh, brackish, or salt water (see Box 2-1).

About 80 percent of the world's trade volume is transported by ship (Peters, 1993). Thus, global shipping is the underpinning of the majority of world trade. Unfortunately, in many instances half of a given voyage must be undertaken in ballast to compensate for the absence of cargo. The etymology of the word "ballast," meaning "useless load" in Middle Dutch, reflects the fact that since time immemorial ship owners have endeavored to avoid using ballast.

This chapter, which provides information on the role of ballast in ship operations, is a necessary prerequisite to the committee's assessment of proposed strategies for managing ballast water and controlling the introduction of nonindigenous aquatic species without compromising ship safety. A brief summary of ship types and ballast systems is followed by an overview of safety issues relating to ballast operations and typical ballast conditions at sea and in port. Mechanisms for the introduction of nonindigenous species into ballast tanks are addressed in Chapter 1.

DIVERSITY OF SHIPS AND BALLAST SYSTEMS

Ballast water is carried by many types of vessels and is held in a variety of tanks or holds. The relative complexity of ballast operations depends on the size, configuration, and requirements of the ship and on the complexity of its pumping and piping systems. Ballast capacity can range from several cubic meters in sailing boats and fishing boats to hundreds of thousands of cubic meters in large cargo carriers. Large tankers can carry in excess of 200,000 m^3 of ballast. Ballasting rates can be as high as 15,000 to 20,000 m^3/h (see Table 2-1).

BOX 2-1
BALLAST DEFINED

Ballast is any solid or liquid placed in a ship to increase the draft, to change the trim, to regulate the stability, or to maintain stress loads within acceptable limits. For the purposes of this study, the term ballast includes the sediment that accumulates in ballast tanks, which may be discharged with ballast water.

Piping is sized so that flow velocities do not exceed about 2.6 to 3m/s, with ballast pump capacities ranging up to 5,000 m^3/h. There is no international standard unit of measurement for ballast; quantities of ballast are variously recorded in metric tons, long tons, cubic meters, U.S. gallons, Imperial gallons, and barrels. In this report cubic meters is used as the unit of measurement; conversion factors are given in the glossary.

Typical vessel types and their ballast needs can be broadly classified as shown in Table 2-1. There is a wide range of ballast tank locations and configurations, as illustrated schematically in Figure 2-1. The capacity, location, and flexibility of use of ballast tanks is a focal point in ship design. Consideration of required drafts and trim, hull loading limitations, and required vertical center of gravity establishes the necessary ballast volume and location. Because of different cargo distributions or fuel and water quantities on board, sister ships can have different ballast needs, even though the locations and sizes of the ballast tanks are identical.

Ideally, ship owners prefer to complete all voyages with cargo. However, many trades and voyages require passage without cargo or in a light-cargo condition. For example, a crude oil tanker or iron ore carrier typically transports a single cargo load between two ports, then returns to its point of origin or another port without cargo. In this empty condition the vessel requires ballast to operate safely—a condition referred to as being "in ballast."[1] In contrast, a container ship may be fully loaded between two ports but may then proceed with only a partial load between the next two ports. This vessel, therefore, sails with some cargo and some ballast, that is, "with ballast." Since fuel costs usually increase with displacement, ship owners tend to use as little ballast as is necessary for the ship's safe, efficient passage when operating either with ballast or in ballast.

TABLE 2-1 Typical Vessel Types, Ballast Needs, and Pumping Rates

Ballast Needs[a]	Vessel Types	Typical Pumping Rates (m^3/h)
Ballast replaces cargo	Dry bulk carriers	5,000–10,000
Ballast required in large	Ore carriers	10,000
quantities, primarily for	Tankers	5,000–20,000
return voyage.	Liquefied-gas carriers	5,000–10,000
	Oil bulk ore carriers	10,000–15,000
Ballast for vessel control	Container ships	1,000–2,000
Ballast required in almost all	Ferries	200–500
loading conditions to control	General cargo vessels	1,000–2,000
stability, trim, and heel.	Passenger vessels	200–500
	Roll-on, roll-off vessels	1,000–2,000
	Fishing vessels	50
	Fish factory vessels	500
	Military vessels	50–100
Ballast for loading and	Float-on, float-off vessels	10,000–15,000
unloading operations	Heavy lift vessels	5,000
Ballast taken on locally in	Military amphibious assault vessels	5,000
large volumes and discharged	Barge-carrying cargo vessels	1,000–2,000
in same location.		

[a]The three categories of ballast needs are not mutually exclusive. For example, a vessel in which ballast replaces cargo may also require ballast to control stability.

SAFETY

Ballast water is taken on board vessels to achieve the required safe operating conditions during a specific voyage or portion of a voyage. Proper ballasting (in terms of the amount of water taken aboard and its distribution) fulfills the following functions:

- reduces stresses on the hull of the ship
- provides for transverse stability
- aids propulsion by controlling the submergence of the propeller
- aids maneuverability by submerging the rudder and reducing the amount of exposed hull surface (freeboard or windage)
- compensates for weight lost from fuel and water consumption

Ballast condition, including when and how much water is loaded, is determined by ships' officers, based on the specific vessel's operating needs and the

[1] Definitions of ballast-related terms are provided in the glossary.

national and international requirements for proper maintenance of the trim and stability of the vessel at sea. The master of the ship is responsible for ensuring that all ballasting operations are executed in a safe manner, commensurate with prevailing conditions (see Box 2-2).

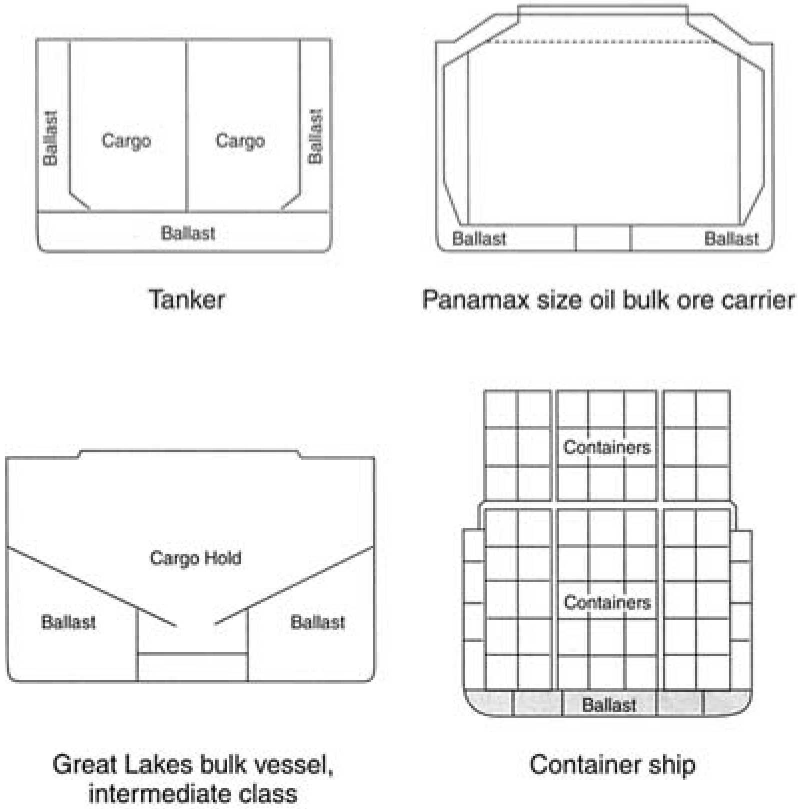

FIGURE 2-1 Typical ballast tank arrangements.

BALLAST CONDITIONS AT SEA

The major purposes of ballasting a vessel for a voyage are to increase its manageability (and safety), particularly under heavy weather conditions; control its draft and trim for maximum efficiency; and control its stability to ensure safe passage. Related factors that determine ballast conditions at sea are summarized below.

Heavy Weather Considerations

Ships must be deep enough in the water to ensure safe passage, particularly in heavy weather. If the bow of the ship is not deep enough, the ship's forefoot (the area under the bow) will emerge periodically from the water surface. This leads to slamming—or heavy impact—of the hull when the bow hits the water with a high velocity on re-entry. Excessive slamming can lead to hull structural damage or even to hull failure and ship loss in extreme conditions. In heavy weather conditions, the ship's master usually chooses to decrease speed, which reduces the rate of occurrence and severity of slamming. Deeper drafts forward will generally reduce the tendency for the ship to slam. Typically, ships ballast to a light-ballast draft in normal weather, then ballast to a deep-ballast draft in heavy weather.

BOX 2-2
SAFETY IS PARAMOUNT

The numerous ballasting requirements applicable to ship safety result in very complex and time-consuming operations for crew members. Ballast operations are performed in a dynamic environment, either at sea or in port, and safety is paramount. The ultimate responsibility for the safety of the ship and its crew always rests with the master of the ship.

Efficient propeller operation usually requires the propeller to be immersed, even in calm water conditions. Thus, if the stern is not deep enough, ballast may be needed to trim the vessel. Further, if the stern draft is not sufficient in rougher sea conditions, the ship's propeller will race (i.e., increase its revolutions per minute) when it emerges from the water and will slow down when it re-enters the water. This causes engine control problems and increased loading on the propeller shafting and machinery. Increasing stern drafts reduces the tendency for the propeller to emerge and, thus, reduces racing. Designs typically seek to achieve a stern draft in heavy ballast of about 80 percent of the load draft.

Accordingly, safe ship operation in heavy weather requires the addition of ballast to designated cargo holds, ballast holds, or tanks to achieve a heavy-ballast load condition (storm ballast).

Sailing with Full Tanks

Ballast tanks used for controlling trim or heel, some fuel oil tanks, and tanks containing fresh water for domestic use, may be partially full at sea, depending on the stability and strength requirements of the ship. It is usually necessary to sail with as many as possible of the tanks on board either completely full or entirely empty. When a tank is not completely full (i.e., "slack"), and the ship heels, the free surface effect of the liquid moves the center of gravity of the liquid in the tank, thus reducing the transverse stability of the ship (see Appendix C). In addition, fluid in a slack tank sloshes around during ship motion, which may lead to excessive loads on the tank/hold bulkheads, frames, or underdeck structure. In severe weather conditions, this could lead to structural failure. Thus, during ballast change at sea, the ballast in a single tank or pair of tanks should be completely changed before proceeding to the next tank or tanks.

Controlling Trim during Voyages

As fuel is consumed during a voyage, the draft and trim of the ship will change. During a long voyage, thousands of tons of fuel may be used. Thus, to keep the hull immersed correctly for maximum efficiency, it is often necessary to take on additional ballast as the voyage progresses. Some ship designs place the fuel tanks so that the ship naturally trims by the stern as fuel oil is consumed, but ballasting may still be required. Ballast capacity and location during a given voyage are established by examining the estimate of fuel to be consumed, weather conditions expected, and the required draft and trim for the arrival port (s).

Transverse Stability Considerations

The transverse stability of a ship is defined as its ability to sail upright and to resist capsizing. To attain proper transverse stability requires careful control of the righting moment of the ship (see Appendix C). Ideally the ship should be loaded and/or ballasted in such a way as to give it an easy rolling period that is neither too fast nor too slow. A vessel that rolls too fast has excess stability (a stiff ship) and has a marked tendency to return to its original upright position quickly. This creates an extremely uncomfortable motion that can exert high loads on the ship's structure and cargo lashings and high sloshing loads in slack tanks. A vessel that rolls too slowly has insufficient stability (a tender ship) and may capsize under heavy weather conditions. When ballast is moved, it creates a condition of slack ballast tanks. The associated free surface effect can lead to a weight shift when the vessel heels that adversely affects the transverse stability of the ship. A more detailed discussion of stability issues is provided in Appendix C.

BALLAST CONDITIONS IN PORT

Ballast operations are carried out in port to maintain ship stability, as discussed above. Ballast operations in port also maintain both the clearance under cargo loading or cargo discharge facilities and the under-keel clearance so the vessel remains safely afloat; maintain the hull bending moments and shear forces within safe limits to avoid the catastrophic damage that can result from incorrect loading; and maintain the ship upright by trimming or heeling the ship. In addition, ballast operations in port establish the efficient ballast condition for the pending voyage.

Ballasting during Cargo Loading and Discharge Operations

Bulk oil carriers (tankers), dry bulk carriers, and most other ships deballast during cargo loading operations and take on ballast during cargo discharge operations (see Table 2-1). A group of ships operate as float-on, float-off platforms where the ship is ballasted down to allow cargo to be floated on board and deballasted to lift the cargo for the voyage. The process is reversed for unloading. The ballast needed is set by the required cargo-deck submergence. Some vessels, such as heavy lift vessels, use ballast to control ship heel during loading operations.

Controlling Drafts and Trim for Port Entry

In the course of normal operations many vessels must alter draft and trim to facilitate entry to ports, berths, or both, at loading and unloading facilities. Both water draft and air draft may be of concern during port entry. Ballast may need to be discharged to reduce water drafts when entering some ports or approaching specific terminals, and it may need to be added to reduce air draft when clearing bridges or when approaching under loading heads at some bulk cargo terminals. These operational parameters can place restrictions on the time and location of ballasting and deballasting.

Safe Longitudinal Loading Considerations

The shear forces and bending moment on the hull of a ship are established by the distribution along the ship's hull of the difference between the light ship weight, together with the cargo, fuel, ballast and other deadweight items; and the supporting buoyancy force. In a seaway, buoyancy support forces are subject to change as waves move along the hull and as the hull moves relative to the sea surface. The structural design of a ship's hull is developed for specific conditions of loading defined in the design process. The ship operator must ensure that the in-service conditions to which the ship is subjected are consistent with the structural design of the ship. The specific location and amount of ballast on board in various conditions can be essential to the ship's safety, ensuring that the bending moment and the shear forces acting on the hull remain within these design parameters. Loading manuals and onboard loading computers are used by ship's officers to monitor the effects of various cargo, fuel, and ballast loading configurations on the draft, trim, and non-wave-induced bending moment conditions experienced by the hull. There are specific conditions when ballast is needed to avoid exceeding these hull loading limits. There are also times when it is not possible to add or remove ballast in particular tanks without exceeding these hull loading limits—in extreme cases excessive loads could cause hull failure and possibly the sinking of the ship.

Controlling Trim and Heel During Cargo Handling

Some vessels, particularly containerships, need to control trim and heel carefully during cargo loading and discharging so that the cargo operations can proceed both safely and efficiently. Some vessels have computerized heel control systems that move ballast between heeling tanks to maintain the vessel within a set tolerance of vertical. Roll-on, roll-off vessels have restrictive draft limits for the use of their ramps. Both the cargo weight distribution at the various intermediate stages of loading and wind heel effects on a light vessel can heel the vessel to the extent that containers will not move in their cell guides.

Ballast Condition for Voyages

When ballasting a ship for a voyage, the crew, under the direction of the master, defines the amount of water required taking into account the loaded condition, route, predicted weather conditions, and the need to complete the voyage in a safe and efficient manner. In the future there may be some possibility of modifying ballast systems in new ship designs for facilitate cleaning and improve the safety of changing ballast at sea, but the complete elimination of ballast is not currently practicable (see Appendix D).

BALLASTING

Ballast water is taken on board using sea chests with ballast pumps or by gravity feed. Sea chests can be located under the ship, on the turn of the bilge, or on the ship's side and are usually replicated on both sides of the vessel (see Figure 2-2). The ballast system usually works in reverse during deballasting, with the water passing through an overboard discharge valve located on the side of the ship's hull. Ballast water loading and discharging operations are usually controlled from a central ballast monitoring/control station and ballast water can be gravitated in or out of a particular tank or hold, pumped in or out, or a combination of these methods can be used. Ballast pumps remove most of the ballast water. In some cases, separate stripping pumps further reduce the amount of water remaining in the tanks. Trimming of the ship by the stern may also be used to aid ballast removal. Despite these efforts, some ballast water and sediment will always remain on board.

The ballast intake is covered with a grate or a strainer plate with small holes, and inboard of the sea chest there is usually a suction strainer. The primary purpose of grates and strainers is to protect the pumping system from foreign objects being drawn in. In some poorly maintained vessels, the integrity of grates and strainers can be compromised, allowing larger organisms to enter the ballast system. The additional use of portable screens to prevent intake of unwanted organisms is unlikely to be practicable for existing vessels but could be an attractive option if incorporated in new ship designs.

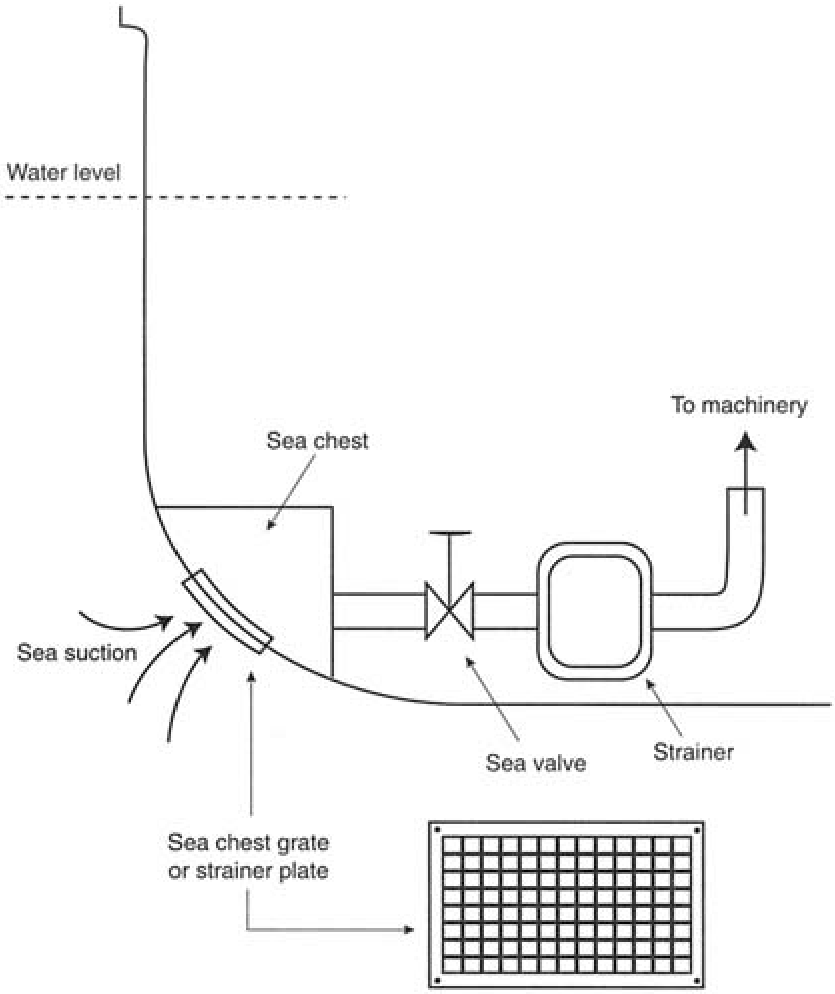

FIGURE 2-2 Typical ballast system.

As was noted earlier, some unpumpable ballast water always remains on board.[2] This unpumpable water may form a virtually permanent layer on the bottom of a dedicated ballast tank, with the concomitant capability of supporting

[2] The amount of unpumpable ballast water remaining on board varies greatly because of vessel diversity. One report notes that vessels claiming to have only unpumpable ballast on board were carrying, on average, 157.7 metric tons of water and sediment (Weathers and Reeves, 1996).

a living benthic community on the tank bottom. A similar situation may exist on vessels that nominally are not carrying ballast. Inbound vessels that have released their ballast water prior to or during cargo loading, and outbound vessels with full cargo loads, may have relatively little ballast water remaining such that the mariner would report a ballasting condition of "no ballast on board."

Sediment frequently accumulates on the bottom and on many horizontal surfaces in ballast tanks. Sediment may include the settled mud (silt and clay) of harbor, port, and estuarine waters, detrital and other flocculent material ubiquitous in shelf waters (but present to some extent in almost all waters), scale (rusted metal shedding off tank walls), and cargo residue. Of 343 cargo vessels sampled from 18 Australian ports, at least 65 percent "were carrying significant amounts of sediment on the bottom of their ballast tanks" (Hallegraeff and Bolch, 1992). Sediment is typically removed every three to five years when the vessel is undergoing special survey or refit work in a dry dock. Sediment is removed more frequently if the buildup warrants the expense.

In ballasted cargo holds, sediment typically is removed by hosing down at the end of each ballast leg before the next cargo is loaded; thus, a portion of the sediment is almost always directly released into the arrival port. The amount of sediment buildup is a function of ship design and operating practice.

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3

Managing Ballast Water

The principles for managing ballast water[1] are similar to the basic principles of quarantine science. The process of managing ballast water should prevent introductions of nonindigenous species, including bacteria, viruses, algae, protists, invertebrates, and fish. An important corollary is that no control options practiced today totally prevent the unintentional introduction of nonindigenous aquatic nuisance organisms through ships' ballast operations. Technologies to achieve this goal need to be:

- safe for a ship and its crew
- effective in destroying potential invading organisms
- environmentally acceptable
- practicable in application
- compatible with normal ship operations
- cost effective

There are measures currently available that can reduce the risk of releases of nonindigenous aquatic organisms into the marine environment. The most effective control method currently in use for ships in international trade involves changing ballast water loaded in port (or taken on board while transiting inshore waters) with ocean water that is loaded during passage between ports of call.

[1] As noted in Chapter 1, ballast water includes associated sediment.

VOYAGE APPROACH

The voyage approach to managing ballast water is a useful means of categorizing the wide spectrum of suggested control options (see Figure 3-1). Three stages in a ship's voyage and related control options can be identified as follows:

- On or before departure. Control is based on preventing or minimizing the intake of organisms during loading of ballast water at the port of origin.
- En route. Control is based on the removal of viable organisms prior to discharge of ballast water at the destination port either by treatment or by open ocean ballast water change. Shipboard treatment could commence immediately upon departure and continue throughout the voyage.
- On arrival. Control at the port of arrival begins when the vessel's master intends to discharge all or some of the ballast water on board. Control strategies are aimed at preventing the discharge of unwanted organisms that could survive in the target environment.

The viability of various control options is dependent on vessel size and type and the upload and discharge capacity of pumping and piping systems. In the future, modified ship designs that (1) minimize the quantity of ballast water discharged, (2) permit safe ballast change at sea under a wide range of operational conditions, and (3) facilitate cleaning of ballast tanks may be part of an overall ballast water control strategy (see Appendix D).

Although proven shipboard systems for treating ballast water are not yet available (see Chapter 4), there are a number of control options that could be undertaken today that would immediately reduce the transport of nonindigenous species by ballast water. For example, vessels could avoid taking on ballast in ports with high sediment loads, in areas of sewage discharge, or in "hot spots" where certain unwanted organisms were known to be present. A plan for managing ballast water, developed in conjunction with the ship cargo plan, would assist the ship's master in adjusting ballast loading and discharging needs to meet constraints on ballasting in these locations. In addition, a requirement for official logs indicating when and where ballast was taken on or discharged would be helpful for implementing existing (and future) strategies for managing ballast water. The following discussion of options for controlling ballast water includes measures that could be taken in the immediate future, as well as methods that require further development.

On or before Departure

Approaches to ballast water control that prevent or minimize the intake of organisms at the port of origin need to take account of ballast requirements for safe ship operation, locations and times of ballasting, and practical limitations on treating ballast water as it is loaded. As the first line of defense to control

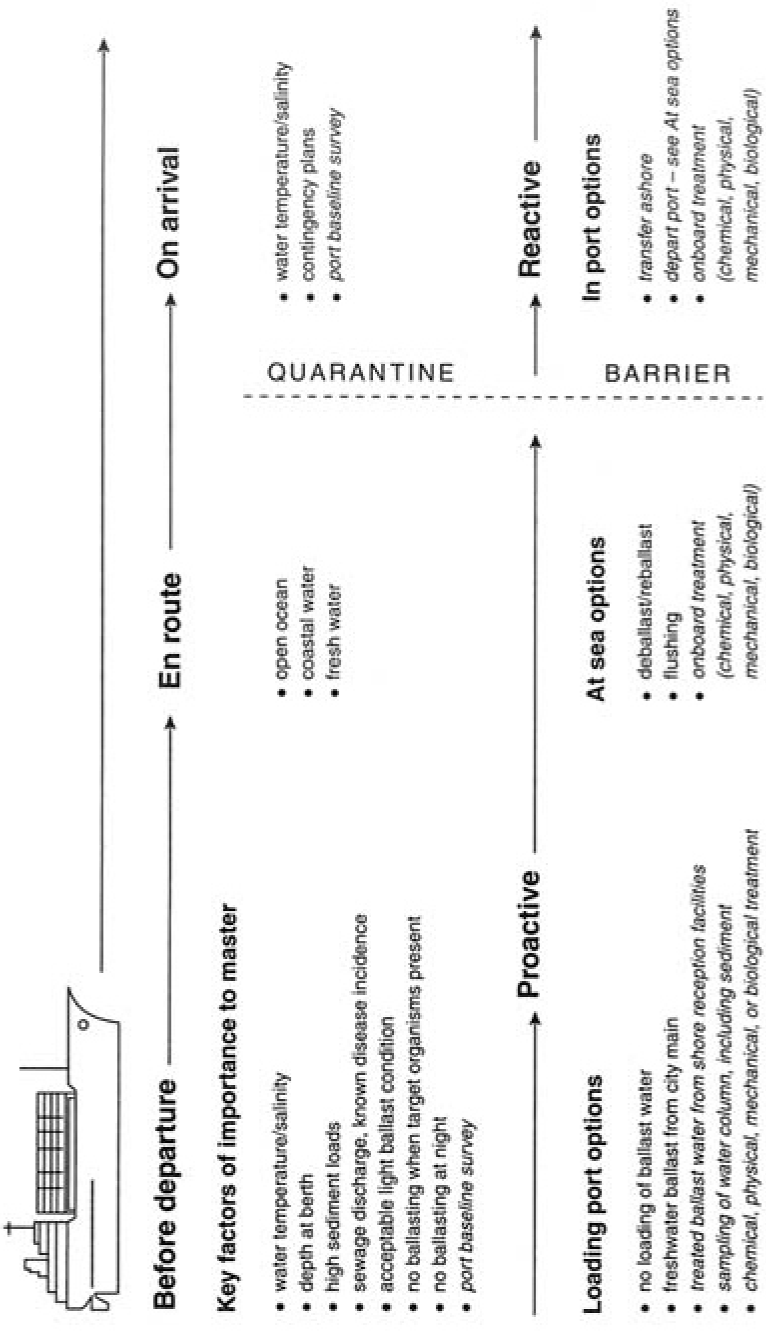

FIGURE 3-1 Voyage approach to managing ballast water. Note: Italics indicate future options

introductions of nonindigenous aquatic species through ballast water, a vessel's master may consider not loading ballast water if the vessel is capable of operating safely and efficiently without it. Locations and times when ballast is likely to contain such organisms include:

- global "hot spots" where targeted organisms are known to be present in the water column
- ports with high sediment loads
- areas of sewage discharge or known incidence of disease
- certain sites at certain times of year, depending on seasonal variations in populations of organisms
- at night, when some planktonic organisms migrate higher up the water column

Despite concerns about nonindigenous species, ships may need to take on ballast water in port to preserve safety. The need for ballast to ensure ship safety during cargo loading and unloading imposes practical restrictions on available control options (see Chapter 2, Ballast Conditions in Port). For example, certain classes of vessels, such as bulk carriers, need to load ballast water simultaneously with the discharge of cargo. Thus, the option of treating ballast water as it is loaded may merit consideration under some circumstances.

Most large ships routinely load or discharge ballast at rates of thousands of cubic meters (metric tons) per hour. Pumping systems associated with ballast movements meters abroad ship are large, and flow velocities may be as high as 2.6 to 3 m/s. These high flows are similar to those encountered in large drinking or waste water treatment plants common in the United States. However, typical units required for these treatment plants are much larger than could be fitted on board a ship.

In addition to handling high flows and volumes, a treatment system used in conjunction with ballast loading operations would be required to remain on standby when not in use. During loading operations in port, for example, the system could be cycling on and off as the ship discharged ballast to accommodate cargo being loaded. This is not an optimum scenario for existing complex water treatment systems, which are designed to operate continuously at a predetermined load factor.

Despite these technical challenges, treating ballast water as it is loaded remains a potentially attractive option because it would obviate the need for controls en route. Thus, the operational hazards accompanying ballast change would be avoided, as would the need for onboard treatment of a sediment/water mixture (see Chapter 4).

Most ballast water is taken on board in coastal and estuarine areas that tend to contain high levels of suspended solids. In some cases, ships taking on ballast are floating very close to the bottom and can scour bottom sediment into the ballast system. As a result, ballast water often contains high concentrations of suspended material, which presents a problem for both the ship operator and the treatment system engineer. Sediment accumulates in ballast tanks in large quantities (hundreds of cubic meters) and is costly to remove and to transport. Suspended sediment also interferes with most treatment systems, whether they are physical separation processes or advanced oxidation processes. In the first case, suspended sediment tends to plug screening systems rapidly, necessitating the use of substantial bypass systems. In the second case, suspended material may shield target species from any treatment process. Thus, treatment efficacy—defined in terms of inactivation of target organisms—may be severely limited in the presence of suspended solids.

En Route

Ships that traverse large areas of open-ocean water have different options for controlling ballast water than ships that traverse inshore and coastal waters. For instance, many ships crossing a large body of open water may have the option of changing ballast water at sea. If ballast can be changed, treating ballast water on board may not be necessary. However, in some cases only a partial or incomplete change of ballast is possible, particularly in bad weather. Thus, changing ballast and treating ballast water on board are not always mutually exclusive.

Shipboard Treatment

Once ballast water has been loaded on board, the ideal mechanism for preventing subsequent introductions of nonindigenous aquatic species is to kill or remove the organisms prior to discharging ballast water overboard. This can be done by chemical, physical, mechanical, or biological treatments, or by any treatment combination. In all cases, the offending organisms or treatment residues must be dealt with in an environmentally safe way before deballasting or subsequent disposal. A detailed discussion and evaluation of possible onboard technologies for treating ballast water is provided in Chapter 4.

Ballast Change

The change of coastal and port ballast water with ocean water is an approach to the reduction of nonindigenous species inoculations.[2] There are two major biological and ecological principles that provide the scientific basis for this control option. First, the probability of reciprocal introductions is virtually nonexistent. The oceanic environment is inhospitable for freshwater, estuarine, and most inshore

[2] It is accepted that ballast change serves little or no purpose for lake carriers that do not travel outside the Great Lakes waterway system, with the possible exception of controlling the spread of localized infestations.

coastal (neritic) planktonic organisms discharged. Similarly, oceanic organisms taken in ballast and later discharged into freshwater, estuarine, or inshore coastal waters encounter hostile conditions and are unlikely to survive. Second, the transport of viable released organisms back to neritic (inshore coastal) waters from mid-ocean by ocean currents is extremely unlikely.

Ballast change can be carried out by two methods (see Figure 3-2):

- pumping out ballast water taken on in ports, estuarine, or territorial waters until the tank is empty, then refilling it with mid-ocean water
- flushing out ballast water by pumping in mid-ocean water at the bottom of the tank and continuously overflowing the tank from the top until sufficient water has been changed to minimize the number of original organisms remaining in the tank

Both options must be determined safe by the crew, classification societies, and flag state authorities before use because of ship design variances. Depending on sea conditions, the ship may become unstable or the allowable forces on the hull may be exceeded (see Chapter 2), with catastrophic results, if the first option is used. If the second option is used, the ballast tank or ballasted cargo hold may be pressurized or the integrity of the ship may be jeopardized.

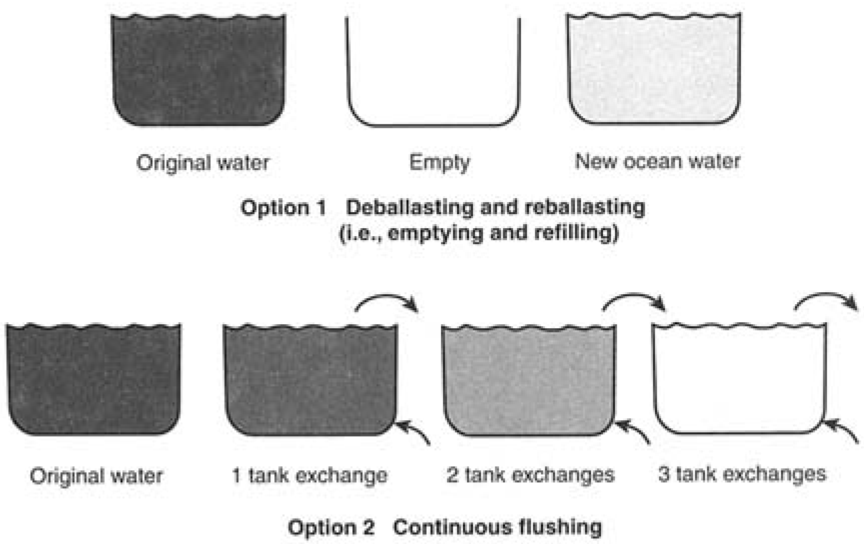

FIGURE 3-2 Basic options for changing ballast water. Note: The effectiveness of ballast water change using continuous flushing has been monitored using a dye tracer. After three tank exchanges, 95 percent of the original ballast water had been changed (AQIS, 1993). Source: Adapted from Rigby and Taylor (1994).

A very limited analysis of possible hazards caused by emptying and refilling ballast tanks at sea was conducted by Woodward et al. in 1992. A later study conducted for the Transport Canada Marine Regulatory Directorate analyzed ballast change operations for a Panamax bulk carrier and a Cape Size bulk carrier (Transport Canada, 1995). The results of that study showed that, although both vessels would meet all relevant stability criteria during a ballast change operation, changes in forward and aft drafts would produce several instances of propeller emergence and an increased risk of forward slamming. The study also found that both vessels would be unable to comply with the Great Lakes Ballast Water Control Guidelines introduced by the Canadian Coast Guard on May 1, 1989.

In addition to the safety constraints that restrict the use of ballast change, the effectiveness of this method for controlling introductions of nonindigenous aquatic species is limited by vessel design and operational considerations. Ballast change can rarely, if ever, remove all original organisms from ballast water. Most ballast pumping systems and tanks are designed to remove as much water and sediment as practicable, but they cannot remove all ballast and associated biota. In addition, voyage passage times or bad weather may not permit a complete change of ballast by either method (deballasting/reballasting or flushing). As noted in Chapter 2, even sister ships must be treated separately because differences in cargo loading will result in differences in the forces acting on the hull. Therefore, ballast change must be evaluated on a case-by-case basis and cannot be required by regulators as a universally viable method to minimize the introduction of unwanted nonindigenous organisms.

Despite the aforementioned difficulties, ballast change is an important component of initiatives that attempt to control the introduction of harmful nonindigenous aquatic species into port and coastal areas by ships' ballast. (Current international, national, regional, state and local initiatives are summarized below.) In some circumstances alternative control options are necessary. For maximum flexibility in managing ballast water during transit, a vessel needs both onboard treatment methods and ballast change. If acquainted with all the accepted options available for a particular voyage, the master would be able to plan ballast operations to minimize the risk of introducing nonindigenous aquatic organisms.

On Arrival

A vessel may arrive in port intending to discharge ballast, but without having performed satisfactory ballast management procedures. If such procedures are deemed necessary by the appropriate authorities, there are two options for managing ballast water on arrival: ballast can be transferred ashore for treatment at shore-based facilities, if these exist; or the vessel may be directed to depart port and use one of the "en route" options for ballast water management. Onboard treatment could conceivably be conducted in port, but at this time there is no known technology that is effective under these circumstances.

Previous experience has shown that shore-based treatment to avoid oil pollution (MARPOL 73/78)[3] is less than satisfactory in many cases because global commitment to establishing suitable facilities is lacking.[4] In the case of shore-based facilities for treating ballast water, some ports will be able to establish facilities, but others will not. Therefore, it is highly likely that ships will still be required to manage their ballast water using onboard treatment or other procedures that minimize the translocation of unwanted species.

In the absence of shore-based facilities for receiving and treating ballast water, a contingency plan must be developed. Such a plan might direct a ship to depart port to discharge ballast water or to change ballast at sea in an area considered safe and environmentally acceptable before returning to take on cargo. When developing contingency plans, port administrations need to be watchful to ensure that this approach to managing ballast water does not become a routine, accepted control option for arriving ships. If vessels routinely depart port to change ballast there could be serious delays in cargo operations, which would, in the end, work to the severe disadvantage of the ship, the cargo owners, and ultimately the port administration.

Shore-Based Treatment and Ballast Lighters

The advantages and limitations of shore-based water treatment facilities have been discussed in two recent reviews (AQIS, 1993; Carlton et al, 1995). Both reviews considered a land-based treatment facility and a mobile "treatment ship" that could accommodate widely spaced berths or be shared between ports. However, treatment facilities on board a "treatment ship" would be subject to the same limitations (except space) as a commercial ship and standardized connections, and piping would be required to transfer ballast water.

In some ports, where there is space, the option of establishing large-scale, shore-based facilities to treat ballast water may exist. Sizing of the treatment process units would depend on the number, timing, and type of ships entering the port. If ballast-water storage tanks were provided such that water did not have to be pumped directly from a ship to the treatment plant, the capacity of the process units could be reduced (AQIS, 1993). The review by Carlton et al. (1995) notes that shore-based facilities would require a potentially expensive industrial infrastructure and supporting administrative framework, neither of which currently exists in the United States. There is also no precedent for recovering associated costs.

[3] The Protocol of 1978 relating to the International Convention for the Prevention of Pollution from Ships, 1973.

[4] Shore-based treatment of ballast water to remove oil residues is conducted at many oil ports, such as Valdez, Alaska, and Sullom Voe in Scotland, where specialized treatment facilities have been constructed within the past 20 to 30 years. Such facilities do not exist in many parts of the world and are not designed to remove or destroy aquatic organisms.

Many oil refineries have dirty ballast water reception facilities that receive oil-contaminated ballast water from oil tankers. These facilities were specifically designed to remove the oil from the ballast water before releasing it to the port water. Such reception facilities were required under Annex I of MARPOL 73/78. It may be possible to modify these facilities to incorporate a ballast water treatment facility to remove unwanted nonindigenous aquatic organisms. Carlton et al. (1995) note that the comparatively few ballast facilities now treating oily ballast from tankers "can only be minimally compared to a ballast water supply and treatment industry on a national scale."

Another possibility is to provide mobile transport facilities (lighters) to transport ballast to a shore-side facility. This would require the transport of large quantities of ballast for some large cargo carriers and could severely limit a ship's ability to ballast or deballast quickly.

Advantages and Disadvantages of Shore-Based Treatment

The main advantages of shore-based treatment are:

- Port (or regional) authorities could operate and maintain the facilities and could routinely monitor them to determine the extent and effectiveness of treatment.
- Operation of a land-based facility permits better control of treatment than under potentially difficult operational conditions onboard ship.
- Waste from the treatment process could be disposed of in an environmentally acceptable manner under the control of an appropriate authority.

The main disadvantages of shore-based facilities are:

- Connecting pipelines would be needed between the treatment facilities and all berths, and every ship would need to have its ballast water pumping system modified (AQIS, 1993). Larger ports would need multiple shore-reception facilities.
- Delays in shipping could occur if the ballast capacity of ships exceeded the capacity of the treatment plant (including storage tanks).
- If ships are capable of ballast change at sea, ship operators would probably elect to use this option rather than shore-based facilities, thus limiting the economic viability of such facilities.

Despite these disadvantages, shore-based treatment remains an option within the amalgam of currently available options for treating ballast water, provided the criteria for safety, environmental acceptability, technical feasibility, practicable operation, and cost effectiveness are met.

CONTROL OPTIONS

The committee considered the possibility of the concurrent development of a plan for loading and discharging ballast water and the ship cargo plan. For example, if a ship is to load bulk cargo of various grades, or different bulk cargoes in different ports, it would be useful to develop an associated ballast water operations plan, taking account of information on locations and times when ballast is likely to contain unwanted organisms (see above). In this way, the master could adjust the requirements for loading and discharging ballast. Even though the plan for managing ballast could be as complicated as the typical cargo plan, this method would provide flexibility in planning for contingencies.[5] The committee agreed that a plan for managing ballast water should be mandatory when target organisms, such as those from global hot spots, are involved.

The various options described earlier complement the plan for managing ballast water because they give the ship operator more flexibility for planning for each voyage and each port of call on a case-by-case basis. To take maximum advantage of this approach, educational and operational guidelines that address each option would be beneficial. In some cases, specific operational procedures would have to be approved in advance by the ships' classification society or flag state administration.

Some specific examples of control options for managing ballast water that may minimize or prevent the unintentional introduction of nonindigenous aquatic nuisance organisms are given below:

- Change ballast water at sea with engine cooling water heated to a temperature in excess of 45°C (110°F).[6] Research has shown that cooling water heated to this temperature is completely free of live microplankton (AQIS, 1993). This is not necessarily an option for treating all the ballast water on board for all micro-organisms or for dealing with large quantities of ballast water. (Onboard thermal treatment is discussed in Chapter 4.)
- Take ballast water on board using high-ballast-water suction if unwanted organisms are known to exist in the bottom sediment. Alternatively, the ship could partially ballast at the cargo discharge berth and finish ballasting upon departure but while still in calm waters.
- Prohibit deballasting in U.S. waters by ships on some voyages when ballast water can be retained on board. Some container ships have computerized plans for discharging ballast water. With careful preplanning, these ships could dispense with discharging ballast in U.S. ports. In other circumstances, ships engaged in liner/break-bulk cargo trades may have enough ballast water tanks to keep ballast water on board during a roundtrip voyage. For example, the ship's ballast water intake can be planned such that alternate ballast tanks are used to carry water picked up in a given U.S. port of discharge later into the same port area.

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[5] Most ships currently plan ballast loading and discharge based on ship strength and stability, without consideration of possible introductions of nonindigenous species.

[6] The quantity of heated cooling water on board a ship is directly related to the horsepower of the main engine.

The examples above do not pertain to all ships and are not candidates for mandatory requirements for managing ballast water. They are given here only as examples of specific methods that can be used to manage ballast water discharges on an ad hoc or case-by-case basis to illustrate the options that can be used to control ballast water operations.

Ongoing activities by international, national, regional, and other organizations aimed at controlling ballast-mediated introductions of nonindigenous aquatic species are discussed below. These organizations have given much attention to controlling introductions of nonindigenous species by ships' ballast operations. The approaches described in this report generally are compatible with options for managing ballast water that are currently under discussion globally and regionally. Since existing regulations and guidelines for managing ballast water are in their infancy, any assessment of their biological effectiveness and of associated administrative procedures is premature at present. Assessments of effectiveness will rely heavily on the results of monitoring ballast and port waters (see Chapter 5).

INTERNATIONAL ACTIVITIES

In June 1991 the International Maritime Organization (IMO), a specialized agency of the United Nations (see Box 3-1), developed voluntary guidelines to prevent the introduction of unwanted aquatic organisms and pathogens through ships' ballast water and sediment. On November 4, 1993, Resolution A.774(18) was adopted by the 18th Assembly of IMO (IMO, 1993). By this resolution the Assembly requested member states to apply the voluntary guidelines to minimize the introduction of unwanted aquatic organisms and pathogens in ships' ballast water and sediment discharges.

The work of IMO is done by committees or subcommittees composed of representatives from member states. For conventions and amendments to conventions, a draft instrument is prepared. This draft is submitted to a conference to which delegations from all states within the United Nations—including states that are not IMO members—are invited. The conference adopts a final text that is submitted to governments for ratification. Implementation of the requirements of a convention is mandatory for countries that are party to the convention.

The first comprehensive anti-pollution convention that related directly to the reduction of intentional and accidental pollution by ships was the Protocol of 1978 relating to the International convention for the Prevention of Pollution from Ships, 1973. This convention, known as MARPOL, addresses pollution from oil, chemicals and other harmful substances, garbage, and sewage. The MARPOL convention, which is currently in force internationally, comprises a set of annexes addressing ship pollution issues. Some of these annexes make reference to separate guidelines that provide detailed technical information. The guidelines can be updated to take advantage of technology developments and improved operating practices without revising the related annex.

BOX 3-1
INTERNATIONAL MARITIME ORGANIZATION (IMO)

The IMO is a specialized agency of the United Nations, chartered in 1948 as the international body devoted exclusively to maritime matters. Since its inception, the improvement of maritime safety and the prevention of marine pollution have been the IMO's most important objectives. The IMO is an organization of member states made up principally of flag states, coastal states, and port states. To achieve its objectives, IMO has promoted the adoption of some 30 conventions and protocols in the past 30 years, and has adopted well over 700 codes and recommendations concerning maritime safety, the prevention of pollution, and related matters.

The Marine Environment Protection Committee of IMO is currently drafting regulations for a new proposed annex to MARPOL 73/78 dealing with the ballast water issue. This annex, which will employ the guidelines strategy, will make use of the guidelines mandatory. The guidelines can be implemented by reference and will be continuously reviewed and updated to take into account improvements in methods for controlling ballast water. The annex probably will not be adopted before the turn of the century.

Codes and recommendations adopted by the IMO assembly are not binding on governments unless they are specifically adopted by reference in conventions and amendments to conventions. However, in many cases, the contents are incorporated into domestic legislation.

When the new MARPOL annex is in force, the ships of those member nations party to the convention will be required to use the guidelines to minimize the introduction of unwanted aquatic organisms and pathogens in ships' ballast water and sediment discharges. In view of the time it will likely take until MARPOL is amended, the United States has acted to stimulate use of the voluntary IMO guidelines by appending them to the U.S. Coast Guard Ballast Exchange Education Program guide for shipping agents in U.S. ports.

There is no international requirement for keeping a log of ballasting operations, other than on tankers where the oil pollution record book includes ballast transfer as a measure to prevent oil pollution. However, an ongoing discussion at IMO on plans for managing ballast water might result in a requirement to maintain a log of ballasting operations. Meanwhile, international attention and coordination on ballast water monitoring and related research continues in forums other than IMO. For example, the first international scientific symposium on measures to reduce the risk of adverse effects arising from the introduction and transport of marine species by ships' ballast water was convened in September 1995 at Aalborghallen in Aalborg, Denmark, as a session of the International Council for the Exploration of the Sea (ICES) 83rd Statutory Meeting. The symposium was co-sponsored by IMO and the Intergovernmental Oceanographic Commission. Some major conclusions of the symposium, many of which parallel the work of the committee (see Chapter 6), identified requirements for international coordination of research efforts, continued research on practical control technologies, increased understanding of the environmental conditions influencing the survival of the diverse aquatic organisms carried in ballast water, and educational programs supporting the implementation of strategies for managing ballast water (ICES, in press).

NATIONAL ACTIVITIES

The United States, Canada, Australia, New Zealand, and Japan are also addressing ballast water control options and issues. Unilateral mandatory requirements for preventing introductions of harmful aquatic nonindigenous species from ballast water are currently in place for the Great Lakes and the Hudson River, Chile, and the port of Haifa in Israel. Following the introduction of Japanese dinoflagellates into its waters, Australia initiated extensive ballast-water studies and began to explore regulatory measures to establish guidelines for managing coastal ballast water.

In 1990, the U.S. Congress enacted P.L. 101-646 (the Nonindigenous Aquatic Nuisance Prevention and Control Act of 1990) aimed at preventing future introductions of harmful aquatic nonindigenous species and controlling existing unintentional introductions. The act contains five basic precepts: prevent unintentional introductions; coordinate research and information dissemination; develop and implement environmentally sound control methods; minimize economic and ecological impacts; and establish a research and technology program beneficial to state governments. The act tasked a new interagency aquatic nuisance species task force with facilitating implementation of these five precepts.

P.L. 101-646 called for mandatory regulations for managing ballast water for vessels that operate beyond the Canadian or U.S. exclusive economic zones (EEZ) and enter the Great Lakes. The act was amended in 1992 to extend the regulations to vessels operating beyond the EEZ that intended to visit a port on the Hudson River above the George Washington Bridge. These regulations (see Box 3-2) allow for alternatives to ballast water change as a control method.

BOX 3-2
U.S. REGULATIONS FOR THE CONTROL OF NONINDIGENOUS SPECIES IN BALLAST WATER IN THE GREAT LAKES

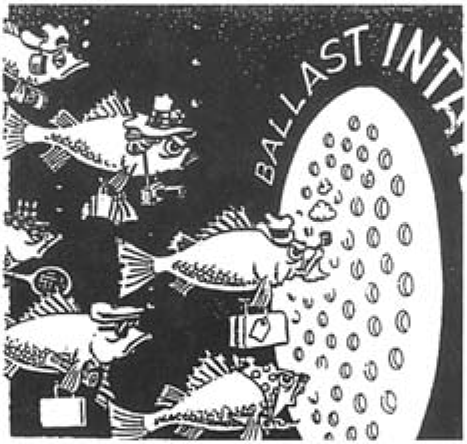
U.S. regulations implementing mandatory compliance with the Nonindigenous Aquatic Nuisance Prevention and Control Act of 1990 went into effect May 10, 1993. The U.S. Coast is the cognizant implementing authority within the United States. These regulations apply to all vessels that have operated outside the EEZ of the United States or Canada and that carry ballast and pass through Snell Lock at Massena, New York—regardless of other ports of call in the United States or Canada. Currently a master of any vessel to which these regulations apply has three options to choose from to comply with the requirements:

- Conduct a change of ballast water at sea beyond the EEZ in a depth of at least 2,000 m. The regulations require that the level of salinity in the ballast water equal or exceed 30 ppt. The salinity of ocean seawater typically ranges from 34 to 36 ppt.
- Retain the ballast water on board during the entire voyage within the Great Lakes. If this option is chosen, the Coast Guard captain of the port may seal the pump control valves leading to any tank or hold containing ballast water to prevent the release of water.
- An alternative, environmentally sound method of ballast water management may be used, but it must first be approved by the U.S. Coast Guard commandant.

Several U.S. agencies have voluntarily heightened efforts to manage ballast water on a national scale. For example, the U.S. Navy has modeled its procedures for ballast water and anchor system sediment after the IMO guidelines. The Navy's procedures apply to U.S. Navy vessels worldwide (Chief of Naval Operations, 1994). The U.S. Coast Guard has taken steps to educate the shipping industry. The U.S. Coast Guard has also begun collecting basic information about whether ships inbound from foreign ports have plans for managing ballast water.

REGIONAL, STATE, AND LOCAL ACTIVITIES

There have been several regional approaches aimed at controlling introductions of aquatic nuisance species by ships' ballast operations, notably in the Great Lakes and Chesapeake Bay. Such initiatives are aimed at guiding those states that wish to cooperatively develop and implement regional plans for managing ballast water. These regional activities have involved a broad range of interest groups, including representatives from shipping ports; the scientific community; and regional, state, and federal governments. Cooperation has been achieved at a regional level outside of legal mandates. The committee judged such cooperation to be an important factor in addressing the problem of nonindigenous species transfer, which is not simply an issue for the shipping industry but has implications for society as a whole. Even if the Coast Guard is ultimately responsible for the implementation of guidelines and regulations, ports, terminal operators, and state authorities have a role to play in their development and in creating processes for their implementation.



"No room at the intake." By Steve Lindstrom. Reprinted with permission from the Seaway Port Authority of Duluth.

Affected vessel owners, agents, ports, and government agencies cooperatively developed and implemented the Great Lakes Maritime Industry Voluntary Ballast Water Management Plan for the Control of Ruffe in Lake Superior Ports (Appendix E). This plan was designed to prevent the Eurasian Ruffe from infesting the lower Great Lakes through ballast water. The plan was implemented on March 18, 1993, to coincide with the opening of the 1993 shipping season. The states bordering Lake Superior have also instituted an aggressive public education campaign aimed at reducing the likelihood that the Ruffe will be spread by other means. Contingency plans have been developed in case the Ruffe becomes established in inland waters.[7]

In 1993, the Chesapeake Bay Program, a regional organization committed to the restoration of the Bay, adopted a policy that lays out framework of cooperative management approaches and public outreach efforts for introductions of aquatic nonindigenous species (Chesapeake Bay Commission, 1992). The policy guides the signatory parties of Maryland, Virginia, Pennsylvania, and the District of Columbia in the development and implementation of management plans for both intentional and unintentional introductions. The Chesapeake Bay Commission, a tri-state legislative commission serving the General Assemblies of Virginia,

[7] During 1995 the Ruffe was discovered in Lake Huron. The ramifications of this discovery are being addressed by the Ruffe Task Force.

Maryland, and Pennsylvania, also helps guide the states in cooperatively managing the Chesapeake Bay. To this end, the Commission convened a ballast water committee and issued a report setting forth a series of recommendations that could be adopted by individual states (Chesapeake Bay Commission, 1995).

Because federal regulatory response has been limited to the Great Lakes and Hudson River, some states have attempted to pass their own legislation or resolutions rather than wait for additional federal action. Four states (California, Washington, Hawaii, and Alaska) have pursued legislative efforts to regulate ballast water discharges, but none has been successful, either because of resistance in their own legislatures or anticipated legal challenges. As a general legal precept, state regulation may not pose undue burden on either interstate (domestic) commerce or enforce a maritime rule that interferes with the federal maritime jurisdiction (international obligations).

INTERNATIONAL FRAMEWORK FOR REGULATION

IMO is the international body under whose auspices international maritime pollution-control and safety agreements are developed. As noted above, the Marine Environment Protection Committee of IMO is currently drafting regulations for a new proposed annex to MARPOL 73/78 dealing with the ballast water issue. Such regulatory coordination by IMO has notable advantages over the introduction of unilateral legislation and regulations by individual nations or by individual states or port authorities.

The regulatory challenge of managing ballast water is heightened by the diversity both of vessels and their ballasting systems (see Chapter 2) and of shipping routes, ports, and associated ecosystems (see Chapter 1). Uniformity in operating procedures and training standards in accordance with a framework grounded in international law will reduce confusion and associated opportunities for human error and will promote safe and economic operation. In contrast, mandatory ballast water control measures at the port or regional level, in the absence of a governing international framework, would lead to a complicated patchwork of differing requirements, which would hinder compliance and effectiveness. Further, it is not clear from an ecological perspective that local controls on ballast water operations would be effective. For example, the closing of particular ports to shipping has been proposed as a possible control measure, despite the severe economic consequences. However, this approach would not be effective since coastal traffic and natural currents would disperse organisms to the closed port.

The above arguments militate strongly in favor of a coordinated, international approach to the development of a regulatory framework for managing ballast water. This approach does not preclude the subsequent introduction of more stringent local requirements that build on a basic, comprehensive international regulatory framework.

AUDITING REQUIREMENTS AND MONITORING

To be effective in practice, any ballast-water control mechanism must be capable of being audited or checked for compliance with standard procedures. Such auditing is an integral part of the process for managing ballast water. Auditing of vessel operations currently is conducted by the U.S. Coast Guard. There is no nationally accepted method for testing or monitoring ballast water and its movement from one location to another. Vessels entering the Great Lakes currently are monitored by measuring the salinity of their ballast water. One of the major impediments to the implementation of ballast water management strategies is the absence of appropriate, proven monitoring procedures. Whether a ship's operator selects onboard treatment or open-water ballast change, the quality of the ballast water arriving in port for discharge must be monitored to ensure that it meets appropriate standards. A reliable monitoring procedure is needed so that both ship operators and regulatory agencies can easily determine when ballast water may be safely discharged in certain regions of the world and when further treatment is necessary. Ultimately, the ship's master must be cognizant of the quality of all the ballast water on board.

Auditing ballast operations can take many forms, including requiring official log entries indicating where and when ballast was taken on board or discharged, what treatment methods, if any, were used, and so forth. Under ideal circumstances, boarding authorities would be trained and equipped to sample ballast water quickly and check it for compliance with standards. The ultimate aim would be to establish compliance-audit procedures applicable to all international and domestic vessels that carry significant quantities of ballast water on board. Such procedures should include both periodic and random inspections.

TRAINING

The introduction of new technologies and equipment for the control and monitoring of ballast water will need to be accompanied by suitable training of personnel, together with educational efforts to raise awareness of the nonindigenous species problem. Ships' officers and crews will need to be trained in the use of new procedures and the use and maintenance of new equipment for treating and monitoring ballast water. Not all candidate ballast water treatment technologies would require the same level of training (see Chapter 4). For example, many crews are already familiar with the operation and maintenance of filtration systems for engine cooling water, which are similar to systems that would be used to treat ballast water. Management and staff of shore-based treatment facilities will also require appropriate training, a will regulatory personnel charged with the administration of and compliance with ballast water guidelines.

RISK-BASED PERSPECTIVE ON MANAGING BALLAST WATER

The total prevention of unwanted introductions of nonindigenous aquatic species cannot be guaranteed. Totally sterilizing ballast water may never be economically feasible or otherwise practical, but implementing a system of ballast water management and controls can reduce the probability that unwanted or harmful introductions will occur. Selecting the appropriate level of risk of introducing unwanted organisms has important implications for worldwide requirements for ballast water management and control.

Current guidelines for controlling introductions of nonindigenous aquatic nuisance species do not identify an acceptable level of risk. For example, avoiding ballasting in known "hot spots," in areas where the sediment content of the water column is high, at night, or at certain times of the year are crude but effective measures for managing risk by reducing the number of organisms loaded with ballast water. Although these measures may be effective, they are required or recommended on the basis of very limited knowledge about the risk of introductions. Therefore, the ecological effectiveness and economic efficiency of control measures cannot be quantified.

The fundamental question that remains to be addressed is what level of ballast water control is effective. Biological science cannot currently answer this question. The answer depends in part upon the receiving country's specific concerns about which potential introductions pose economic, ecological, human health, and other risks. In addition, it is not known how many individuals of a given species are needed to establish a viable, self-reproducing population at a new site. Even if this number were known, it would not be consistent from one receiving environment to another.

Issues such as these can be addressed by risk analysis. Risk analysis is used in many settings as a strategic tool for setting priorities and optimizing management and control measures. In the United States, for example, risk assessment is used to establish safe levels of exposure to carcinogens and other toxic chemicals. The Aquatic Nuisance Species Task Force is developing a generic risk analysis for nonindigenous aquatic organisms (Risk Assessment and Management Committee, 1995). In Australia, the coastal water guidelines working group is developing a voyage risk assessment and management process. The proposed risk-based approaches to managing ballast water use quantitative risk assessment methodology to combine a determination of the likelihood of introduction of a specified unwanted organism with an assessment of the economic and social impact resulting from the introduction (see Box 3-3). Lessons learned from successful efforts that use risk analysis as a strategic decision aid underscore the importance of standardizing methods and assuring that assumptions and methods are clear to all (NRC, 1994).

Even though detailed scientific information, such as species-specific data on probabilities of establishment, is generally lacking, risk analysis methodology can help decision makers in two ways. First, it can assist regulators in establishing appropriate levels of protection by helping them understand and balance technical, economic, and social factors. Second, when a specific organism is of concern, risk analysis methods can help evaluate alternatives and optimize the selected control strategy. Thus, a probabilistic risk analysis based on limited available

BOX 3-3

THEORETICAL ELEMENTS OF RISK ASSESSMENT

A risk assessment combines two components—the likelihood of an adverse event and the resulting consequence if the event occurs. These two major components are further divided into seven basic elements that serve to focus scientific, technical, and other relevant information into an assessment. In the case of introductions of nonindigenous aquatic organisms, the basic elements are as listed below (Orr, 1995).

Group I: Assess Probability of Establishment[8]

- Nonindigenous Aquatic Organisms Associated with Ballast Water. Estimate the probability of the organism being in the ballast water or the associated sediment. The major characteristic of this element is whether the organism shows temporal and spatial patterns consistent with its presence in arriving ballast water.
- Entry Potential. Estimate the probability of the organism surviving in transit. Characteristics of this element include the organism's physiological and biological potential to survive in ballast water and its life-cycle stage during transit.
- Colonization Potential. Estimate the probability of the organism colonizing and maintaining a population. Characteristics of this element include the organism's potential to survive and reproduce in the new environment. (Survival encompasses the presence of an appropriate physical-chemical regime, predators, and many other elements.)
- Spread Potential. Estimate the probability of the organism spreading beyond the colonized area. Characteristics of this element include the organism's ability for natural dispersal, the potential for human-mediated dispersal, the development of races or strains, and the estimated range of probable spread.

Group II: Assess Consequences of Establishment

- Economic Impact Potential. Estimate economic impact if established. Characteristics of this element include human health, economic damage to aquaculture (i.e., if disease, parasite, or pest), damage to natural resources (e.g., harvesting, fishing), effects on subsidiary industries, damage to structures (e.g., shipworms and gribbles) and costs to control the organism.
- Environmental Impact Potential. Estimate environmental impact if established. Characteristics of this element include ecosystem destabilization and reduction in biodiversity.
- Perceived Impact (social and political influences). Estimate impact on social and/or political concerns. Characteristics of this element include aesthetic damage, reactions to health concerns, and political repercussions.

[8] As noted in Chapter 1, biological scientists currently cannot answer many questions relating to the fate of discharged organisms and the likelihood of their establishment.

data (Englehardt, 1995) can be a useful indicator of cost-effective management strategies. Its principal value in decision-making is as a strategic tool, illuminating the dimensions of a problem and the implications of alternatives. As knowledge of the marine environment, potential threats, and control technologies improves, (making more extensive and reliable data available for risk assessments), risk analysis will become more accurate in establishing levels of protection and more effective as a planning aid and a decision-making tool.

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4

Shipboard Treatment Options

This chapter identifies various methods of treating ballast water that are safe, practicable, technically feasible, cost-effective, and environmentally acceptable. The main focus is on treatment processes that are feasible for onboard use to control species transfer in ballast water.[1] The basis for many of the candidate technologies originates in the wastewater treatment area, although the uniqueness of shipboard ballast applications was a major factor in the committee's assessment. A discussion of treatment issues and options is followed by a listing of candidate shipboard treatment technologies. The committee's methodology for data collection and technology evaluation is described, followed by an assessment of candidate systems; the most promising options are addressed in some detail. Supplementary information on some of the candidate technologies is provided in Appendix F, as appropriate.

TREATMENT ISSUES

Treating ballast water to free it from potentially harmful invasive species is a challenging problem. Many different species potentially can be transferred to areas where they become invasive and a nuisance; therefore a single preventive treatment for all such species is difficult to identify. Ships may travel great distances between ports or visit many ports of call throughout the course of one voyage. Depending on the amount of cargo carried and the weather conditions

[1] For the purposes of the present discussion, changing water in a ballast tank by continuous flushing or deballasting and reballasting is not considered to be a shipboard treatment process. Ballast change is addressed in Chapter 3.

encountered, the movement of ballast on and off a ship can be highly variable (see Chapter 2). Substantial power and space limitations on ships, together with safety concerns for the vessel and its crew, make onboard treatment options complex. Space on board any ship is at a premium, and some ships are more seriously constrained with respect to space than others.

Defining effective treatment scenarios is complicated by the variability of ships, shipping routes, and ports. Lakes and waterways typically contain large quantities of minerals but have low chloride-ion concentrations. Oceans are perhaps less complicated because of their chemical consistency worldwide when they are away from the continental shelf. The pH and salinity of seawater are kept relatively constant by a complex balance of chemicals. The unpredictable mix of ocean and fresh water in estuaries, shallow tidal bays, and inlets, where major port facilities are located, tends to create a zone rich in nutrients and resulting marine life. A short list of water parameters that must be addressed by systems for treating ballast water comprises temperature, salinity, pH, dissolved oxygen, suspended solids, and biological constituents.

Ships' ballast tanks and cargo/ballast holds represent a unique challenge for treating water due to the high flow rates, large volumes, organism diversity, and ballast water residence time. It appears that with currently available technology one overall onboard treatment scenario will not be effective for all vessels carrying ballast water in and between various regions of the world. As discussed in Chapter 3, a range of preventive measures, including onboard and shore-or port-based methods for treating ballast water, will be needed to address the problem of controlling introductions of nonindigenous aquatic nuisance species. Earlier reviews of options for treating ballast water, such as Canadian Coast Guard (1992), AQIS (1993), and Carlton et al. (1995), provide more detailed discussions of these methods.

TECHNOLOGIES FOR TREATING BALLAST WATER

Shipboard treatment methods are the most flexible for managing ballast water. For this reason, the committee determined that treating ballast water on board ships will be the ultimate solution to reducing introductions of nonindigenous aquatic species. The following sections describe candidate technologies and methods for evaluating them.

Treatment technology options can be incorporated during three different phases of ballast operations: (1) during ballasting at the cargo discharge port; (2) during the voyage, between ports; and (3) during deballasting at the cargo loading port (see Figure 3-1). Each of these scenarios has significantly different constraints with respect to treatment options. In the first and third scenarios, large quantities of water must be treated in a short period of time, while water is taken on board or discharged and flow rates through the treatment system are high. In the second scenario, water resides in the ballast tanks or cargo/ballast holds between ports; more time is available for treatment; and flow rates through the treatment system may be lower. In addition, water can be recirculated until the number of organisms inactivated is sufficient to provide the appropriate level of protection. As noted earlier, ships can discharge ballast water at an extremely high rate (upwards of 20,000 m^3/hr at flow velocities up to 3 m/s), with resulting drawbacks for inline treatment in terms of system capacity and associated space and power requirements. However, inline treatment during ballasting/deballasting is potentially more effective in inactivating large organisms throughout the entire sediment/water mixture than onboard treatment. In the latter case, the sediment fraction settles to the bottom, and at least a two-phase system (water column and sediment fraction) is present. Therefore, even treating ballast water at a lower flow rate for a longer time period may not easily achieve inactivation in the sediment fraction.

The committee identified 10 candidate technologies for shipboard treatment:

Filtration Systems. Filtration systems are widely used in municipal and industrial applications. Systems designs are determined by the size and type of particles to be removed. Filter systems require periodic cleaning, either manually or using automatic backflush systems.

Oxidizing and nonoxidizing biocides. Oxidizing biocides, notably chlorine and ozone, are widely used in waste-water treatment. Organic structures, such as cell membranes, are destroyed by the addition of strong oxidizers. Nonoxidizing biocides include a large inventory of compounds commonly used in industries for treating the growth of organisms in cooling tower water and other areas where large amounts of biological growth or sediment accumulation occur. Nonoxidizing biocides work in a manner somewhat analogous to pesticides by interfering with reproductive, neural, or metabolic functions of organisms, such as by inhibiting respiration.

Thermal techniques. High temperatures are commonly used to sterilize water in a wide variety of applications.

Electric pulse and pulse plasma techniques. The application of a pulsed electric field or an energy pulse to water can kill organisms. Electric pulse systems generate an electric field; pulse-plasma systems deliver a high energy pulse to an inwater arc mechanism and generate a plasma arc in water.

Ultraviolet treatment. Treating water with ultraviolet energy to inactivate bacteria is a well-established technology. Ultraviolet irradiation in the fluid at wavelengths of approximately 200 nm can destroy cellular components.

Acoustic systems. Acoustic systems use transducers to apply sound energy of specified amplitude and frequency to water to be treated. The sound energy causes cavitation, and the resulting mechanical stresses disrupt cells.

Magnetic fields. Water to be treated is passed through a magnetic field of specified flux that is generated by ferromagnetic or electromagnetic devices. The biological and chemical effects of magnetic systems are not well understood, but it is thought that the organic and inorganic constituents of living organisms in the water are altered by the magnetic field.

Deoxygenation. Most potential aquatic nuisance species require oxygen to survive. When oxygen is removed from the water, many organisms (but not cysts, spores, or anaerobic bacteria) are killed. Some organisms that require oxygen can survive short periods of anoxia, but they are usually inactive under such conditions. Oxygen can be removed from water by purging with an inert gas or by binding oxygen to a chemical additive.

Biological techniques. Biological techniques to control unwanted species include the introduction of additional organisms that are predators, pathogens, or competitors of the species of concern. Such techniques have proven useful in the control of certain insect pests when the biocontrol species develops self-sustaining, reproducing populations. Biological treatment also includes the use of modern biotechnology methods to modify the genetics of the organism of concern.

Anti-fouling coatings. Anti-fouling coatings on hulls reduce biological fouling by contact toxicity, ablation or surface activity. The vast majority of coatings used today rely on toxicity or ablation, or a combination of the two. Surface-active systems are marketed as "fouling release" coatings, but their use is limited because they are expensive.

The committee's evaluations and details of the most promising technologies are discussed in the following sections.

COMMITTEE'S EVALUATION METHODOLOGY

Once the treatment problem was defined, the committee developed a list of candidate technologies, drawing in part on wastewater treatment methods. A treatment options query developed by the committee combined a list of technology requirements and capabilities with shipboard application considerations. On the basis of this questionnaire, technology vendors and research organizations were invited to provide data for typical shipboard treatment systems. These data were used by the committee in assessing candidate technologies. All technologies were required to meet safety and effectiveness criteria before being evaluated further. At the conclusion of this assessment, the candidate technologies were grouped into three categories: (1) promising options, (2) options with possible limited application, and (3) other options.

Treatment Options Query

The committee developed the ballast water treatment options query provided in Appendix G as a basis for gathering information on technologies for treating ballast water that were potentially suitable for shipboard application. The type of information needed to assess candidate technologies was determined based on the requirements and constraints discussed in Chapters 2 and 3, information gathered by the committee (see Appendix B), and insights derived from the practical shipping experience and technical knowledge and expertise of individual committee members. The major technology requirements, capabilities, and application issues are discussed below in the context of the committee's evaluation criteria. For any candidate technology, the effectiveness in destroying potential aquatic nuisance species for the volumes of water and flow rates required for shipboard ballast water treatment, and the associated operational safety for the crew and ship, are of primary importance.

The committee's query about options for treating ballast water defines two ballasting scenarios: System A—flow rate of 2,000 m^3/h and tank volumes of up to 25,000 m^3, with residence times as short as 24 hours; and System B—flow rate of 20,000 m^3/h and tank volumes of up to 25,000 m^3, with residence times as short as 24 hours.

The residence time (i.e., maximum time available to treat ballast water) for both systems is defined to be a minimum of 24 hours, reflecting practical constraints imposed by voyage times. Many voyages are likely to be of several days duration; therefore, a treatment time of 24 hours would permit operational flexibility and would be broadly applicable to diverse vessels and trade routes. Flow rates vary considerably with vessel type as discussed in Chapter 2.

Data Collection

The committee held two technology workshops in May and August 1995 in Duluth, Minnesota, and Washington, D.C., respectively, to gather data on candidate technologies for treating ballast water from equipment suppliers, technology developers, and research organizations (see Appendix B). Representatives from these bodies were invited to give presentations to the committee addressing the salient features of water-treatment technologies as applied to ships' ballast, using the committee's query on options for treating ballast water as a guide. Responses to the query were obtained through correspondence with equipment suppliers, technology developers, and research organizations. Product literature and papers from the scientific and technical literature also provided information about treatment options (see Appendices F and G).

Evaluation Criteria

The committee identified a series of parameters for rating technologies that could be used to treat ballast water onboard ships. As noted throughout this report, safety is of overarching importance when assessing strategies for managing ballast water. Further, any such strategy is worthwhile only if it is effective in reducing the likelihood that nonindigenous aquatic nuisance species will be introduced. Therefore, the committee used safety and effectiveness as the first two gates in evaluating technologies. Only systems that were effective for the broad spectrum of organisms typically found in ballast water (see Chapter 1) and deemed safe for the ship and crew were evaluated in more detail. Because ballast water volumes, pumping rates, and engine room arrangements vary significantly from ship to ship, the type and size of a vessel influence the choice of a ballast water treatment system (AQIS, 1993). Thus, the committee made no attempt to select optimum treatment technologies for specific situations, such as for vessels operating in the Great Lakes, but rather identified promising candidates for shipboard use.

The availability of proven commercial treatment systems could provide an important starting point to avoid delays in applying technologies. Given the time and resources necessary to develop a technology from laboratory scale through demonstration projects to commercial status, the adaptation of existing industrial equipment to the shipping industry is a potentially attractive short cut. Although most of the equipment considered by the committee is available commercially, few systems have been used in marine applications. The reliability and maintainability of available equipment, which are extremely important for ship operators, remain to be demonstrated in a shipboard environment. Using commercially proven treatment technologies is attractive in the short term; however it will probably take many years to implement ballast water control practices on the majority of vessels. In the long term, there will be opportunities to develop new, cost-effective systems tailored to specific shipboard conditions.

Power consumption is another important consideration for shipboard applications; treatment systems require power to operate. Power on board ship is limited, and providing more power capacity to treat ballast water may not be practical.

Chemical residuals may be created when treating fresh water and sea water. These residuals can be complex organic chemicals and may or may not be regulated. For example, chlorine is an effective oxidizing biocide, but excess residual oxidant may be subject to controls in some shore locations (Christian et al., 1995). The committee determined that treatments resulting in the least environmental impact are the most attractive.

Most ballast operations involving the loading or discharging of large volumes of water are conducted when a vessel is in port. As noted above, attempts to treat large volumes of ballast water "instantaneously" during ballasting or deballasting in port are extremely challenging. The capability to treat ballast water en-route over the period of a voyage would reduce the capacity requirements and associated costs of treatment systems. Recirculating ballast water during a voyage to increase treatment effectiveness might be practical for some techniques.

For assessment purposes, cost was divided into two components: the physical plant and crew size. Given the lack of precision in most capital cost estimates received from equipment suppliers and developers, the committee considered cost for equipment and installation on an order of magnitude basis. The cost of adapting industrial systems for marine applications is quite high in many cases. Crew size is important in the overall cost of operating a ship. Therefore, if an additional crew member is needed to operate a treatment system, this option will not be acceptable to ship operators.

Practical limitations on the size and complexity of ballast water treatment systems depend on ship type and trade. In general, the optimum system is the smallest treatment unit with the fewest auxiliary support systems. Since ships are built to carry maximum cargo, non-earning space such as engine rooms, ballast tanks, and accommodations is reduced to a minimum. In particular, engine rooms tend to have very limited space for additional equipment, although the most convenient location for a treatment facility would be in or adjacent to the engine room in which the ballast pumps are located, which is usually at the lowest level of the ship.

System maintenance must be kept to a minimum, especially during voyages. A system for treating ballast water must be simple, reliable, and easy to use. Systems that require extensive, time-consuming maintenance—possibly under difficult conditions at sea—are not suitable for treating ballast water on board ships.

Ease of monitoring relates to both the operation and evaluation of treatment effectiveness. Automated systems that combine monitoring and control of the treatment process will be necessary.

Candidate Ranking

The committee ranked candidate technologies using the evaluation criteria shown in Table 4-1. All of the technologies considered by the committee met the safety requirements for shipboard application. Although marine applications have not been demonstrated in all cases, the committee determined that there were no inherent features of the candidate technologies that would preclude safe operation of a shipboard system to treat ballast water. In some cases, special precautions will be necessary to protect ship personnel. For example, the plasma used for pulse-plasma treatment produces a very high pressure shock wave that expands and works against the surrounding water; suitable screening around the treatment system would be required. Similarly, the high voltage part of electric pulse treatment systems would need to be encapsulated to ensure that there were no high electric fields outside the volume of ballast water being treated.

The committee grouped the candidate technologies for treating ballast water into three major categories: (1) promising options, (2) options with possible limited application, and (3) others. Technologies in the first category require some

TABLE 4-1 Evaluation Matrix for Shipboard Treatment Technologies.

			Commercial use					Cost				
	Safety	Effectiveness	Industrial	Marine	Power	Chemical residuals	Recirculation[a]	Plant	Crew size	complexity	Size, Maintenance	Ease of monitoring
Oxidizing biocides												
halogen	+	+	+	+	+	–	+	+	+	+	+	+
ozone	+	+	+	–	–	– saltwater + freshwater	–	–	–	–	–	+
Nonoxidizing biocides	+	+	+	+	+	–	+	+	+	+	+	–
Filtration systems												
media	+	++	+	–	+	+	+	+	+	–	+	+
screen	+	++	+	+	+	+	+	+	+	+	+	+
Thermal treatment	+	+	+	–	–	+	+	+	+	+	+	+
Electric pulse and pulse plasma techniques	+	+	–	–	–	+	–	– –	–	–	+	–
Ultraviolet treatment	+	–										
Acoustic systems	+	–										
Magnetic fields	+	–										
Deoxygenation	+	–										

Note: Key to ratings: + good; – poor; technologies judged to be markedly superior or inferior in a category are designated ++ or – – respectively.

[a] + indicates that recirculation of ballast water improves the efficacy of a treatment technology.

engineering development to optimize systems for shipboard use. Appropriate demonstration projects may be helpful in providing performance data as a basis for further system improvement and assessment of different options. Technologies in the second category require further research and development (R&D) before they can be considered promising candidates for use on board ships. Such R&D would provide additional data on which to base assessments of anticipated shipboard performance. Technologies in the third category do not appear promising at present, although the results of further R&D could alter this assessment.

The committee limited its evaluation to the generic problem of reducing the number of aquatic organisms in ballast water using a single treatment technology. The many possible technology combinations, such as filtration followed by ultraviolet or biocidal treatment, were not evaluated. Nonetheless, the committee recognizes that investigation of technology combinations would be fruitful in addressing specific ballast water control problems.

PROMISING OPTIONS

The committee considers filtration, as well as the addition of biocides (excluding ozone) and thermal treatment, to be relatively mature technologies with the potential for adaptation to treating ballast water on board ships.

Filtration Systems

The physical separation and removal of organisms above a certain size from ballast water could be achieved during ballasting operations using a shipboard filtration system. This appears to be the most promising technology for onboard treatment. Filtering ballast water as it is loaded is a potentially attractive option that would prevent or minimize the intake of unwanted organisms, thereby obviating the need for subsequent ballast change or further onboard treatment.[2] Filtration systems can be designed to remove target organisms from ballast water; however, detailed engineering will be needed for adequate filtration (organism removal) that would provide the appropriate level of protection. The high flow rates and volumes associated with loading (and discharging) ballast present a particular challenge. Also, the complexity and cost of filters increase as the quantity of material removed from ballast water increases (smaller particles). Filtered organisms could be concentrated and stored on board ship and disposed of at a shore-based facility or discharged back into the water if regulations permit. The options for onboard filtration systems are either mesh strainers or deep media filtration.

[2] As noted earlier, maintenance of grates and strainers in a ballast system is important for preventing the uptake of larger organisms.

Coarse strainers are routinely incorporated in shipboard machinery to prevent the intake of large objects into the shipboard systems. However, when the effective opening of screens is reduced to remove small organisms, such as those in the range of 10 µm,[3] plugging or fouling rapidly occurs. Strainers have the disadvantage of being a simple layer-separation technique: once material has been deposited on the screen, the flux of water through the mesh declines rapidly. In water treatment processes where this approach is used, large areas of filtering screen are required to maintain a working flux for any period of time. Generally, backup facilities are included so that a continual flow stream can be achieved despite rapid plugging of strainers.

Recent advances in strainer technology have addressed the above problems, and continuously cleaned screening systems are now commercially available. For example, self-cleaning strainers with automatic control systems incorporate cleaning cycles that can be activated by differential pressure or on a time cycle. Debrisladen dirty fluid enters the large bottom chamber of the strainer and flows upward, passing through the sealed screen element. Unwanted materials are trapped inside the screen. Backwash cleaning is accomplished using the pressure differential between the in-flowing line pressure and the atmosphere. A hollow, full-flow, backwash arm that extends the full length of the screen element and is piped to the atmosphere rotates slowly inside the screen. When cleaning is required the automatic backwash valve opens the system to the atmosphere, causing a high-velocity reverse flow across the isolated section of the screen. Dirt and debris are flushed from this segment of the screen into the backwash piping. During the backwashing cycle the main flow is uninterrupted and continues to be strained in the normal manner (see Figure 4-1).

Other developments in filtration technology may offer advantages for treating ballast water on board ship. For example, flow-through centrifugation systems can separate particles prior to filtering to reduce filter clogging. New wedgewire filtration systems have high flow rates and are cleaned by scraping, rather than backwashing, which eliminates the need for storing and treating backwash water and thereby reduces the overall size of the filtration unit.

Another way to circumvent the problems of simple screening systems described above is to use deep media filters. Media filtration is one of the most common processes for treating water. Media filtration systems for shoreside application are simple to design and operate and have proven reliable for many years. When used to treat ballast water on board ship, a typical pressure filter could produce high quality water at a flux of at least 24 m^3/hr per m^2 (10 gpm/ft^2) of filter area, depending on the media coarseness. Assuming this typical flux, a ship with a ballast flow of 5,000 m^3/h would require a filter approximately 200 m^2 in area by 2 m deep. Clearly, the size of such units would preclude their use on board a ship.

[3] 1µm = 10^{-6} m = 1 micrometer.

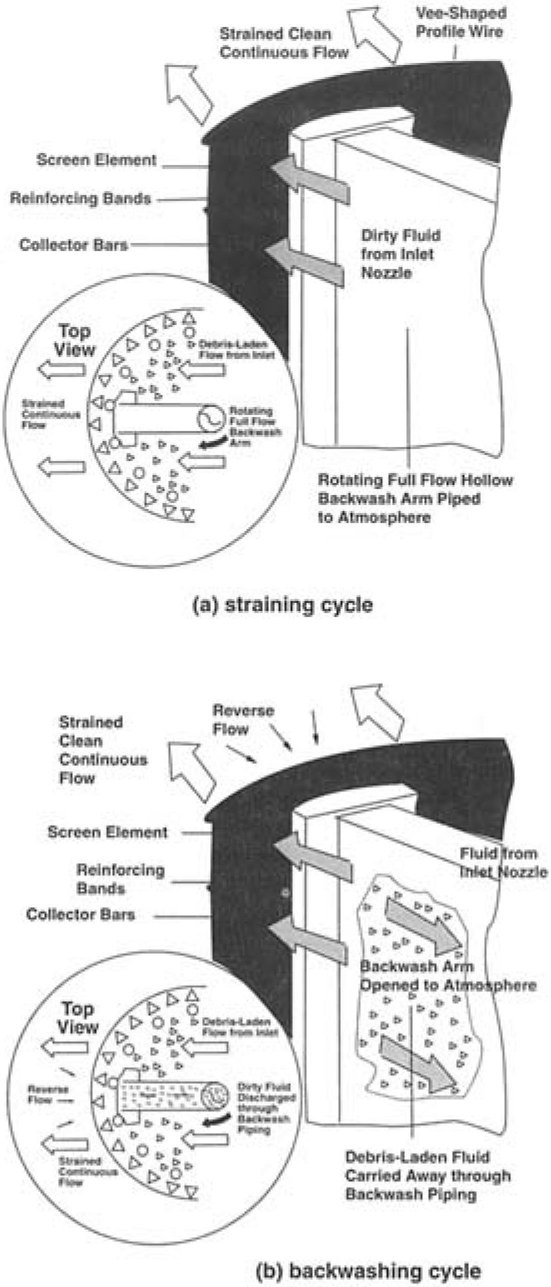

FIGURE 4-1 Operation of a self-cleaning strainer. Source: Adapted from Hayward Industrial Products, Inc. (1995).

More efficient mixed media filters can be readily designed, and precoating of filters can be included to further enhance their effectiveness. Media can be adjusted to remove particles as small as 1 to 5 µm in diameter, if necessary. These filters would be easily cleaned using conventional backwashing mechanisms, and the backwash material could be stored on board in a separate tank prior to discharge overboard in some open ocean area. Innovative approaches such as the fuzzy filter (Tchobanoglous and Caliskaner, 1995) may permit higher flow rates per unit area, thereby reducing the size of media filtration units and rendering them feasible for shipboard use.

Media filtration treatment would remove not only all organisms larger than 5 to 10 µm in diameter but also most of the sediment load in the ballast water. Therefore, all organisms, whether residing in the sediment or dispersed in the water column, would be effectively separated from the ballast water during the ballasting operation. Because deep media filters are highly reliable and do not plug rapidly, the ship would be able to use them on an intermittent basis during ballasting operations. The time-dependent plugging of deep media filters can be monitored easily by measuring the pressure drop or head loss across the media, and a shipboard system could be cleaned or backwashed when time permitted. Installation of deep media filters on board ships would not be a severe problem as a retrofit. Bypasses from the main ballast water system would need to be rerouted through the filter, but neither the piping system nor the ballast tanks themselves would need to be substantially modified.

A potential advantage of an inline media-filtration system is that ballast water would be treated effectively regardless of when it was loaded. Thus, discharge of treated ballast water could occur at any time in any location without increasing the risk of introducing nonindigenous aquatic nuisance species. Further investigation of this option for treating ballast water is needed to determine the relationships between achievable flow rates and selected media for effective organism removal. Deep media filtration systems could be designed for individual ships and ship classes to optimize shipboard use.

Several earlier assessments of the possible use of filtration systems for treating ballast water are available. In general, the findings and conclusions of these studies are consistent with those of the committee. An assessment for the Australian Quarantine and Inspection Service (1993) of ballast water treatment technologies concluded that media filtration is effective in removing the majority of marine organisms from ballast water, although the large footprint of existing units precludes shipboard use. Strainers were found to be relatively compact, simple to operate, and amenable to retrofit on existing vessels, but they were found to have limited effectiveness because many organisms of concern are smaller than the existing strainer slot sizes and can pass through the treatment system. The design of a filtration system for a typical large bulk carrier is discussed in the Australian study, and space requirements and estimated costs are provided for a range of strainer systems capable of handling flow rates up to 4,000 m^3/h.

A study for the Canadian Coast Guard (1992) concluded that the physical removal of organisms by filtering may be an effective stand-alone treatment process or may be used in conjunction with other technologies, such as chemical oxidation or ultraviolet sterilization. Space constraints for media filtration units were identified as an issue, as were high flow rates during ballast uptake and discharge. A recirculation type treatment system was also considered in the Canadian study. The reader is referred to the original report for cost estimates and technical details of systems with different pumping rates and strainer slot sizes.

In another recent study of ways to prevent organism intake in ballast water by filtration (Carlton et al., 1995), a two-stage system using woven mesh screen filters is considered. The first filter would remove most of the larger zooplankton; the second filter would remove most of the smaller zooplankton and most of the large and medium-sized phytoplankton. The relative merits of woven mesh and wedgewire filters and discussed, as are space requirements, mesh size, and order of magnitude costs.

Biocides

Perhaps the most compelling reason to consider biocidal treatment is its ease of application. Biocides could be added to ballast water by metering concentrated solid chemicals or they could be generated electrolytically from sea water. These two methods of applying biocides are currently used on board ships, although not for treating ballast water. Alternatively, simple chemical injection pumps, feeding on line with the main ballast pumps, could routinely add a measured amount of premixed liquid biocide during any ballasting operation. The turbulence within the pumping system would ensure complete mixing of the biocide with the sediment and water column, resulting in efficient inactivation of target organisms. Chemical feed systems would require small amounts of power to pump concentrated bulk solutions to the ballast system. Electrolytic generation systems would require significant amounts of power, typically in excess of 200 kW. In addition, in-situ generation requires large and expensive equipment costing $400,000 to $800,000.

Biocides are among the most widely used industrial chemicals, and there is a large body of scientific data on their use in waste-water treatment. Effective biocide concentrations are typically in the range 1 to 5 mg/l (ppm). Dose levels and contact times need to be determined for effective treatment of aquatic nuisance species. However, if doses are similar to those used for waste-water treatment, only 5 m^3 of biocide would be required for each million cubic meters of ballast water to give a 5 mg/l biocide concentration. Therefore, even large ships carrying thousands of cubic meters of ballast would be required to carry only a few cubic meters of biocide per voyage.

The effectiveness of many biocides is quite simple to monitor: others would require biological indicators to ascertain their level of effectiveness. There is no general, automated monitoring method currently available that could be easily applied on board ship.

Biocide treatment units are relatively simple, although their size could be an issue when retrofitting existing vessels. Units can be designed to require little maintenance, and the greatest burden to the crew would be the filling and monitoring of bulk solution tanks.

Chemical addition for inactivation of micro-organisms has been reviewed recently (Carlton et al., 1995). In general this approach has been dismissed for many reasons including the following:

- reluctance to add any compound to water that might be discharged back to the ocean
- uncertain effectiveness of biocides in achieving inactivation of the target organism(s)
- handling of chemicals on board ship
- compliance with discharge regulations for such chemicals in certain areas of the world

Although these concerns are real, they can be addressed by appropriate research, development, and demonstration activities. Addition of selected biocides may be the most economic solution to achieving the desired goal of inactivating target species.

The safety issues associated with handling chemicals on board a ship may be of concern. Ships routinely carry hazardous industrial compounds and lubricants because they are needed for ship operations. Personnel responsible for handling these compounds are well trained and would be able to adapt to handling other materials without serious constraints. The concentrations of chemicals needed to treat ballast water should be small, and storage requirements may be insignificant. The residual chemicals left in a ship's ballast tanks following treatment and the possibility of corrosion of piping, pumps, and structure need to be evaluated.

Oxidizing Biocides

Decades of studies have demonstrated that, in general, chlorine is an effective biocide. Its specific application for ballast water will require data on the required concentrations and contact times for different categories of organisms —ranging from bacteria and viruses to adult crustaceans and fish—and relative to water flow rates and/or tank volume and water residence time.

Electrolytic chlorination creates active chlorine by passing an electrical current through water containing chloride ions. The chloride ions in brackish water and seawater are used in this process. Chlorination units are comparatively small and used on many ships for biofouling control of seawater cooling systems. A typical unit can treat 7.5 m^3/min (450 m^3/h) at a concentration of one mg/l of oxidant. The use of chlorine gas would be inappropriate for enclosed spaces such as on board ship, but calcium hypochlorite or sodium hypochlorite could be used for treating ballast water. It is well known that the addition of a powerful oxidant such as chlorine to seawater can generate toxic compounds (byproducts) due to the oxidation of halogens (Cl^-, Br^-, I^-). This issue needs to be addressed in the context of various options for treating ballast water.

Nonoxidizing Biocides

Reviews of water treatment conducted in the past have focused on the use of oxidizing biocides. However, as noted above, there is a large inventory of nonoxidizing biocides that are used by industry for the effective control of a wide variety of organisms. An example is the group of glutaraldehyde-based chemicals used in industrial water treatment. The limited reactions of nonoxidizing biocides with compounds in the water may be a possible advantage for ballast water treatment. The residuals generated by nonoxidizing biocides generally decay fairly rapidly into nontoxic byproducts. Thus, treated water might not pose a substantial environmental hazard if it were discharged in large quantities.

Thermal Treatment

The use of waste heat from a ship's propulsion and service cooling is an attractive option for the inactivation of organisms in ballast water because (1) waste heat from ship propulsion and onboard equipment may be used to raise the temperature of water and (2) no chemical byproducts or residuals are discharged (Rigby and Taylor, 1993). Additional piping would be needed to pump ballast water through the existing heat exchangers. To destroy most organisms, ballast water would need to be heated to temperatures in the range 35°C to 45°C (95°F to 113°F) and held there for a set period of time. Investigations of the relationships between treatment temperature and time needed to kill or inactivate certain organisms are continuing (Taylor, 1995).

A number of critical factors will probably limit the practicality of thermal treatment to certain vessels on specific trade routes:

- Length of voyage. Some voyages will be too short to permit heating the water to the required temperature or holding the temperature for the required period.
- Volume of ballast water requiring treatment. There is a limited amount of energy available from waste heat sources. Thus, there are constraints on the volume of ballast water that can be treated.

- Ambient water temperature. The heat input needed for thermal treatment can be reduced significantly where water temperatures are at tropical or summer levels (30°C or higher). The heat loss due to ambient water temperatures outside the hull must be considered. Due to low ambient water temperature, ballast tanks located along the hull shell may have a higher total heat input than those adjacent to cargo.
- Specificity to target organism(s). Higher organisms, such as fish, are more easily killed by thermal treatment than are microbes. Studies will be required to determine the effectiveness of heat treatment to specific target organisms.

Further discussion of thermal treatment is provided in Appendix F.

Technology Demonstration

The promising technology options described above—filtration, the addition of biocides (excluding ozone), and thermal treatment—are currently the most attractive for shipboard demonstration. However, the selection of a technology for demonstration will require an analysis of voyage features such as trading patterns and ports of call. For example, thermal treatment is unlikely to be chosen for short voyages because of the time needed to heat and treat ballast water. The results of the committee's assessment indicate that filtration with state-of-the-art strainers is likely to be the most widely applicable option for treating ballast water on board ships. Shipboard demonstration would provide an opportunity to resolve engineering issues associated with the installation and operation of a strainer system on an existing vessel. Regardless of which technology is chosen for demonstration, a control tank will be needed to establish a baseline against which to compare the results of ballast water treatment. Ideally the treatment and control tanks should be of similar configuration. In addition, it will be necessary to incorporate appropriate sampling and monitoring procedures to determine the effects of treatment (see Chapter 5).

OPTIONS WITH POSSIBLE LIMITED APPLICATIONS

The committee determined that ozonation and electric pulse and pulse plasma technologies are potentially safe and effective methods for treating ballast water, although their current status renders them unsuitable for immediate shipboard applications. Nonetheless, limited applications may be possible in the future. The transition of ozone treatment systems from industrial to shipboard applications is a major challenge. Further development of electric pulse and pulse plasma systems for land-based applications should provide more information regarding the suitability of these technologies for shipboard use.

Ozonation

Ozone is an oxidizing biocide used for treatment of potable and industrial process waters. Environmental concerns regarding the use of chlorine have resulted in increased use of ozone as a biocide. Since ozone is an unstable gas that quickly decomposes to oxygen, it must be generated as needed by passing air or oxygen between a high-voltage discharge gap. Large capacity ozone generation units are not currently used for marine applications. Industrial units are relatively complex and bulky and require compressed air sources for the oxygen separator systems and cooling water for the ozone generator. Ozone generators have demonstrated good reliability in industrial applications, requiring about 10 hours of maintenance per month. However, the successful operation of these generators depends on the quality of the feed gas supply, adequate cooling, and a constant, relatively clean electrical power source. In addition, ozone systems have some serious materials problems, including increased corrosion rates of some alloys and deterioration of seals. Given the uncertainties associated with shipboard operation, the committee assigned negative ratings to ozonation for maintenance and crew impact. In salt water (brackish and sea water), ozonation produces the same residuals as chlorination.

Electric Pulse and Pulse Plasma Techniques

Electric pulse and pulse-plasma treatments have been grouped together since both inactivate organisms in a similar manner. Both methods have been successfully demonstrated in the laboratory, and prototype demonstrations are planned. Applied electrical voltages for these systems are in the 15 to 45 kV range, with pulse durations on the order of 1 μs. Although the power requirements for prototype systems are relatively modest (10 to 50 kW, large energy sources would probably be needed for systems capable of treating large volumes of ballast water. Neither the electric pulse nor the pulse plasma process produces toxic chemical residuals, but a pulse power system would generate gaseous decomposition products, notably carbon dioxide. Theoretically, pulses of electricity through seawater could generate chlorine, although none has been detected during laboratory tests of electric pulse systems.

Given the relatively immature status of both the electric pulse and pulse-plasma technologies for treating water, the costs of developing systems suitable for shipboard application are likely to be high, with resulting high equipment acquisition costs. Because both systems are automated and do not require attended operation, their technical complexity should not be a serious disadvantage if the mean time between equipment failures is long and repair can be achieved by replacement. Electric pulse and pulse-plasma systems are currently being designed for long lifetime and low maintenance. However, in the absence of supporting performance data from commercial equipment, there is considerable uncertainty about the practical implications of operating and maintaining these systems. For this reason, the ratings for complexity, ease of monitoring, and crew impact given in Table 4-1 are negative. Further discussion of electric pulse and pulse plasma systems is provided in Appendix F.

OTHER OPTIONS

The committee judged four candidate treatments—ultraviolet, acoustic, magnetic, and deoxygenation—to be inappropriate for shipboard treatment of ballast water since these methods have not been proven effective for a broad range of freshwater and marine organisms. Two other techniques, biological treatment and antifouling coatings, were not evaluated in any detail by the committee because their disadvantages clearly outweighed their advantages.

Ultraviolet Treatment

Ultraviolet treatment is effective in destroying micro-organisms, but not in removing or inactivating higher organisms and cyst or spore stages of protozoa, fungi, microalgae (including dinoflagellates), and macroalgae (AQIS, 1993). In addition, the effectiveness of ultraviolet disinfection is greatly reduced in water containing suspended matter due to absorption and screening effects.

Acoustic Systems

The use of underwater acoustic energy sources (including ultrasonics) to destroy or deter various aquatic species has been demonstrated on a laboratory scale, but the effects appear to be dependent on frequency and species, with no general effectiveness over the wide range of organisms likely to be found in ships' ballast tanks. Ultrasonic frequencies around 20 kHz kill or inactivate bacteria and fungi but not higher organisms. Lower frequency acoustic signals deter fish, although the deterrent frequency is species dependent. High-intensity acoustic sources can shatter the shells of juvenile zebra mussels and lead to the lethal disintegration of veligers. Further details of investigations of acoustic treatment are given in Appendix F.

Magnetic Fields

Magnetic treatment of water on a laboratory scale has been effective against calcareous shell-forming invertebrates, notably zebra mussels, and has undergone significant development for this application. However, the treatment mechanism is not understood and the effect of magnetic treatment on marine micro-organisms and vertebrates is unknown. The method has not been used to treat sea water.

Deoxygenation

Oxygen deprivation (or deoxygenation) is toxic to a range of fish, invertebrate larvae, and aerobic bacteria but is ineffective against anaerobic bacteria and cyst and spore stages, including dinoflagellate cysts, and would provide only a partial solution to killing the range of aquatic species likely to be found in ballast water.[4]

Biological Techniques

Whether biological techniques are effective in removing, reducing or altering living organisms in ballast water and sediment remains theoretical. The addition of new species is unlikely to act as a successful control agent against the wide diversity of microbial animal and plant life that may be present in ballast water. The issue of the transport and release of the added species must also be addressed. Using genetically engineered organisms is also unlikely to provide a solution for the ballast water problem in the near future. The committee did not evaluate biological remediation in detail.

Anti-fouling Coatings

The committee did not consider anti-fouling coatings to be suitable for controlling introductions of nonindigenous species because the surfaces of ballast tanks and the organisms that settle on these surfaces represent only a small fraction of the total problem. Ballast water is a suspension of organisms, and the bulk fluid must be treated to prevent introductions of nonindigenous species by discharged ballast. A coating could be formulated that was highly loaded with toxic material and would release lethal concentrations of biocide into the water. However, this coating would have a short lifetime, and the treated ballast water would probably be toxic and require treatment prior to discharge.

New types of surface-active anti-fouling coatings are being introduced into the market in response to environmental concerns over paints containing copper and tin. The surface-active systems are nontoxic and rely on flow velocity to remove loosely attached fouling. These paints do not prevent fouling and are not appropriate for ballast tanks.

[4] The survival of zebra mussels and Asian clams under conditions of anoxia (oxygen deficiency) has been investigated in the context of research and development aimed at finding environmentally sound methods of controlling zebra mussels (see, for example, Matthews and McMahon, 1995).

DISCHARGE TO THE ENVIRONMENT

Any treatment process used to render ballast water safe for discharge creates some form of residual. If chemical biocides are used, either chemical residuals or reaction byproducts will be generated. If a physical separation process, such as filtration, is used, the material collected from suspension must be discharged. If waste engine heat is used to heat ballast water, the temperature of the discharged ballast water will be substantially higher than the ambient water. All of these factors must be considered when developing a treatment plan.

Treatment with biocides may be of concern because the residual biocide in the water that is discharged into a harbor could be toxic to local organisms. Although residual biocides could have lethal effects if present in high concentrations in the immediate vicinity of a ship using biocidal ballast water treatment, they also could have deleterious sublethal effects on organisms further away. In addition to concerns about the biocide itself, treating water that contains organic materials can result in the formation of a variety of organohalogen molecules. Some of these, such as trihalomethanes, can be mutagenic and carcinogenic, as well as persistent in the environment; others with low water solubility are likely to accumulate in bottom sediment and could become a source for bioaccumulation of toxic chemicals in the local aquatic food web.

Release of heated water from ballast tanks may be of environmental concern because the hot water would be lethal to organisms living immediately near the vessel. Organisms located further away would not encounter lethal temperatures but would, nevertheless, be subjected to additional stress and elevated oxygen requirements; at the same time, available oxygen would be reduced because warm water holds less oxygen than cold water. Thermal releases from ships are not currently regulated, although other sources are controlled. Legislation related to thermal releases is directed primarily at power plants that use local water to cool their machinery and continually release heated water back into a river or estuary. The continuous releases from power plants are a much greater source of heated water than sporadic discharges from ships using thermal ballast water treatment. Furthermore, if ships heated their ballast water during the initial days of a voyage, the water would probably have cooled by the time it was discharged; therefore it would have even less environmental impact.

Perhaps the most environmentally benign discharge from a system for treating ballast water consists of suspended solids washed from filters. Material released from periodically backflushing a media filter or continuously washing a membrane filter is a more concentrated version of what was originally in the local water (planktonic organisms and suspended sediment particles). The nature and concentration of materials in the backflush are predictable and would need to be evaluated only in areas of known contamination. The return of these constituents to the water at their site of origin should be of environmental concern only when toxicity has been defined.

The effectiveness of options for treating ballast water must be monitored to ensure that the risk of introductions is being reduced and to verify that operators are complying with regulations. Monitoring is essential from both regulatory and biological perspectives. Many of the candidate treatment technologies reviewed by the committee have been used to treat waste water, and proven monitoring techniques are available. Automated systems are preferred for shipboard use because of demands already placed on crews and operators. These issues are discussed in the following chapter.

SUMMARY

Based on the committee's evaluation of a wide variety of technologies for treating ballast water, the committee determined that there are no off-the-shelf technologies currently available suitable for use on board ship without some redesign and modification. Filtration, the addition of biocides (excluding ozone), and thermal treatment are currently the most promising options for shipboard application. Filtration using state-of-the-art strainers will probably be the most widely applicable approach. However, many detailed engineering issues associated with the installation and operation of a strainer system on a vessel must still be addressed. The committee's finding that there is no universally applicable option currently available for shipboard treatment of ballast water further highlights the need for diverse approaches to managing ballast water, as was noted in Chapter 3.

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5

Monitoring

Monitoring of ballast water has two major purposes in the context of current efforts to control introductions of nonindigenous aquatic nuisance species. First, monitoring is needed to audit ballast water control methods and check for compliance with regulations or guidelines; therefore it is an integral part of the ballast water management process. Second, monitoring is a research and development tool that permits assessment of the effectiveness of ballast water treatments, allows increased understanding of the nonindigenous species problem, and may assist in developing plans to manage ballast water. The use of monitoring for auditing is likely to become increasingly important as implementation of ballast water guidelines becomes more widespread (see Chapter 3).

Compliance with existing mandatory requirements for changing ballast water prior to entering the Great Lakes is checked by measuring salinity (see Chapter 3). It is the committee's understanding that the requirements in the Great Lakes—and other future regulations—could never be satisfactorily enforced without supporting monitoring protocols. "Spot check" procedures will be needed to indicate (either directly or indirectly) whether the densities of organisms, numbers of species, numbers of specific non-native species, or other such indicators in discharged ballast water have been reduced to the required levels, in the same way current checks at ports and airports serve to enforce compliance with quarantine regulations. Monitoring methods used for such "quarantine checks" will need to address issues of verification, accountability, and responsibility and must be supported by appropriate record keeping.

As noted in the preceding chapter, the committee determined that there is currently no off-the-shelf technology (i.e., technology transferable without modification) capable of completely sterilizing ballast water cheaply and effectively, while also meeting criteria for safety, compatibility with ship operations, and environmental acceptability. Thus, the degree of effectiveness of treatment technologies needs to be measured, particularly during the evaluation of prototype systems. Monitoring ballast water before and after treatment will permit a quantitative assessment of treatment effectiveness. Ultimately treatment effectiveness will be tailored to meet the levels for ballast water discharge defined by regulatory authorities. Monitoring is also important as a research tool to enhance the present limited understanding of the biology of introductions, thereby facilitating the development of effective ballast water management strategies, including a plan for managing ballast water. For example, the presence of dense populations of one or more nonindigenous species of concern could indicate to the master that ballast should not be taken on unless absolutely necessary. Monitoring will also aid in assessing the effectiveness of regulations and guidelines for managing ballast water.

This chapter provides a discussion of the issues associated with monitoring ballast water, whether for auditing or R&D purposes. As with ballast water treatment, shipboard monitoring appears to offer the greatest flexibility, although other possibilities are addressed. Opportunities exist to measure a wide range of ballast water parameters—in addition to salinity—that might be helpful for monitoring purposes. The committee has identified promising approaches, both near term and long term, and has also considered levels of monitoring that might be needed in conjunction with different options for managing ballast water.

Many monitoring procedures and approaches appear promising, but none has yet been used routinely on board ships. Like the candidate technologies for treating ballast water discussed in Chapter 4, shipboard application of monitoring systems introduces additional requirements and constraints on equipment and its operation in comparison with land-based industrial applications. The characteristics of an effective shipboard monitoring system for supporting strategies of managing ballast water can be summarized as follows:

- allows rapid data collection
- permits unambiguous detection of unwanted biological material or indicator organisms
- is safe, rugged, and relatively inexpensive to install and operate
- occupies minimum space, allowing monitoring to be performed in situ aboard ships without impeding other onboard operations
- allows the necessary monitoring to be performed as quickly as possible, so as not to put undue burden on the ship's crew
- permits effective monitoring by personnel with minimum training
- requires a minimum of complex procedures, such as chemical extraction

These characteristics may not be realized in a single automated procedure, and some compromises may be necessary to achieve a workable monitoring method. As discussed below, the monitoring method in any given situation will be closely tied to the methods for controlling and managing ballast water to mitigate risk effectively.

MONITORING SCENARIOS

Vessels arriving at a load port can be in one or more of three ballast conditions:

- Category 1. No ballast change conducted. The vessel arrives with water as ballasted in the port-of-origin or of unknown or mixed origin(s).
- Category 2. Ballast change conducted. The vessel arrives with some proportion of the original water having been changed in the open ocean. Arriving water can range from original water diluted with open-ocean water to almost entirely open-ocean water with traces of original water remaining.
- Category 3. Onboard ballast treatment conducted. The vessel arrives with some or all of its ballast water having been treated in some fashion using physical, chemical, or mechanical techniques, as described in Chapter 4.

A vessel could reflect one or more of the aforementioned conditions because its ballast tanks may contain ballast water from different regions. Thus, different ballast tanks may have been subjected to different treatments. Category 2 (ballast change conducted) represents the most probable ballast treatment scenario because, subject to safety constraints, a ballast change is the most effective treatment option currently available on board vessels. Changing ballast water will quite possibly remain the principal option available in the foreseeable future, unless international bodies agree to more stringent regulations.

In general, category 1 vessels (no ballast change) are likely to present a greater risk as potential inoculators of nonindigenous species than category 3 vessels (onboard treatment). Although most category 1 ships would be considered "higher risk" vessels, exceptions may occur when vessels are transiting climatic extremes, when they ballast in polar waters and deballast in tropical waters, for example, or when they move between fresh water and salt water.

ALTERNATIVES TO SHIPBOARD MONITORING

The discussion in this chapter focuses on shipboard monitoring. However, in some instances it may be impractical or too expensive to install onboard monitoring systems. It has been suggested that a vessel might take ballast water samples at the ballast load port and forward them to the destination port for analysis. Samples (including replicates) would need to be taken using specialized equipment and an appropriate, approved methodology because it is difficult to collect representative samples of ballast water, including the sediment. Samples would then be sent by air freight to registered facilities capable of testing ballast water and sediment samples to internationally acceptable criteria. At present no such testing facilities exist, and advanced biological analysis involving taxonomic identification to species level is both costly and time-consuming (see below). However, in principle, if shore-based analysis indicated that some form of treatment was required, the vessel could be notified accordingly. If the voyage passage time were long enough, treatment could be performed in transit.

A simplified version of this "sampling and dispatch" approach has been used by the Australian Quarantine and Inspection Service in the case of an identified chronic carrier of toxic dinoflagellate cysts operating between Japan and Australia. Extending the "sampling and dispatch" approach to a range of organisms of concern is a significant challenge in terms of both sampling and testing. In addition, critical ballast introductions—such as the Asian river clam in San Francisco Bay—would not have been recognized as significant potential invaders if they had been found and identified in ballast water samples prior to their introduction.

Under some circumstances, ports may choose to monitor their water to provide additional reassurance about the effectiveness of strategies used to manage ballast water in reducing the risk of introductions. For example, some port-water sampling studies have been conducted in Australia to determine the presence or absence of potentially harmful organisms that could be transmitted to other Australian ports (Kerr, 1994). Formal certification that a ballasting site (e.g., cargo discharge port) is, and continues to be, free of a given species requires a rigorous, continuing, scientific program (Carlton et al., 1995). Studies would need to be updated every three to five years—and possibly more frequently—to determine whether a species that was previously absent had been introduced.

Baseline sampling of ports for specific organisms to standardized, internationally accepted criteria would be helpful in determining the risk associated with a voyage between specified ports. The port of ballast water uptake could provide information that would assist vessel owners and operators in deciding upon the ballast water management or treatment methods needed during transit to meet requirements at the receiving port. This procedure could assist regulating authorities in more effective monitoring of possible introductions of a species known to be of concern. This approach would also require a costly, continuing program.

LEVELS OF MONITORING

The committee considered levels of monitoring for vessels in categories 1 and 2 (no ballast change conducted and ballast change conducted). When vessels have undertaken specialized onboard ballast treatment (category 3), monitoring of the method's effectiveness will be sensitive to the treatment class (see below). The three proposed levels of monitoring are as follows:

TABLE 5-1 Approaches to Monitoring

Options for managing ballast water	No change of ballast water	Open-ocean ballast change	Treating ballast water onboard
`` r i s k d e c r e a s e s ````			
Likelihood of scenario occurring	Currently most probable scenario.	Most probable scenario for most vessels within near future.	Possible in the near future if mandated.
Condition of ballast water	Original, as ballasted at port of origin, or unknown.	Ranges from diluted ballast water from port of origin to fully changed ocean water.	Organisms removed and/or inactivated by various treatment methods.
` ` ` ` monitoring effort decreases ` ` `			
Monitoring approach	Monitoring complex because many original organisms present. Start with level II/ III unless transiting climatic extremes.	Levels I, II, and/ or III as necessary to determine that water meets required standards.	Monitoring dependent on treatment method (s)

- Level I. Log of change events and basic water quality parameter descriptions
- Level II. Basic bioactivity and/or indicator species description
- Level III. Advanced biological or chemical analyses

Each of these levels of monitoring requires increasingly higher numbers of personnel, levels of expertise, and expenditures to conduct the analyses indicated below. Level I monitoring is the simplest and least costly; level III is the most complex and expensive. Levels I and II are designed to be conducted on board vessels at sea, using automated equipment (although manual measurements could easily be made). Level III monitoring would probably require an onshore laboratory, using current technology.

Monitoring would be conducted at the lowest level necessary to demonstrate that ballast water meets required standards (see Table 5-1). Failure to meet criteria for effective risk control at one level would necessitate more sophisticated and costly monitoring as defined in higher levels.[1] For example, vessels that have not changed their ballast water are not likely to be able to use level I monitoring approaches to establish with confidence that the risk is acceptable. They would require level II or level III analyses—with some potential exceptions, as discussed previously. Thus, although "no action" is the least costly option for managing ballast water, this option would require extensive monitoring to establish

[1] Such criteria may be sensitive to vessel type, voyage history, and other factors.

that the ballast water meets acceptable levels of risk. In contrast, treating ballast water on board requires investment in equipment and crew training, as well as operational expenditures. However, the associated monitoring procedures would be simpler and could potentially be integrated with the treatment system to provide continuous feedback on treatment effectiveness.

It is probably inevitable that ships taking on ballast water in estuaries will take on sediment. Monitoring approaches need to address the combination of water and sediment. Monitoring the sediment phase is discussed later in this chapter, following the discussion of monitoring water.

Level I Monitoring

Level I monitoring consists of (1) an examination of the ship's logs and records of where and how much ballast water was initially loaded and where and how much of it was changed, accompanied by (2) continuous monitoring of basic physical-chemical water quality parameters, such as turbidity, salinity, temperature, concentration of dissolved oxygen, and pH (see Table 5-2). These parameters can be monitored by automatic, online equipment that provides continuous readouts for subsequent data storage or for direct transmission to shore. Alternatively, all of these parameters could be measured concurrently by handheld equipment at regular intervals.

TABLE 5-2 Basic Physical-Chemical Water Quality Parameters

Indicator	Definition	Potential significance for ballast water monitoring
Salinity	Amount of dissolved salts in water (reported as parts per thousand sodium chloride or as specific gravity).	Could indicate extent to which port water was changed with oceanic water.
Turbidity	Amount of light-reflecting material in suspension in water.	Could indicate concentrations of plankton and suspended sediment.
Temperature	Degree of heat.	The survival potential of ballasted organisms may be determined in part by (1) changes in temperature from voyage start to finish and (2) the temperature difference between ballast uptake and discharge ports.
Dissolved oxygen	Amount of oxygen dissolved in water.	May indicate general ability of ballast water to support living organisms.
pH	Level of acidity or alkalinity in water, as measured by the negative logarithm of hydrogen ion activity.	May indicate differences between port (estuarine) and oceanic water

Records of ballast water operations are currently kept aboard the vast majority of vessels (Carlton et al., 1995). Thus, examination of ships' logs and records (containing mandatory information) for monitoring purposes would not impose any additional burden on the shipping industry, and it could be used in conjunction with basic water quality parameter measurements to verify that ballast had been changed prior to arrival at port. The basic parameters indicative of water quality are readily measured using commercially available instruments and test kits; reliable measurement of pH, conductivity, dissolved oxygen, and temperature is available using a single probe for analysis. Both microprocessor-controlled and digital instrumentation packages can be interfaced with a computer or data-logger for continuous analysis, and many commercial units have been field tested that are suitable for marine applications. Turbidity and concentrations of specific chemicals can also be analyzed using colorimetric and amperometric techniques. Instruments designed for use in process streams can provide continuous measurement of water quality parameters necessary for ballast treatment technologies. Most of these systems are priced between $500 and $2,500, excluding installation costs.

Turbidity may currently be the most useful indirect indicator for establishing the presence of port or inshore water as opposed to open-ocean water; low turbidity would indicate the lack of dense biological populations, such as algal blooms. Measurements of turbidity also reflect relative concentrations of undesirable plankton and suspended sediment. Since it is likely that some sediment will be present at the bottom of the ballast tanks, the results of turbidity measurements can be greatly influenced by sampling location.

Ships arriving from ports and harbors known to be active sites of infestation by known nuisance species may, in addition to the Level I monitoring outlined above, be sampled to check for the presence of the species in question. This would require impounding a vessel until its ballast water had been rigorously examined, unless a "sampling and dispatch" approach could be implemented.

Level II Monitoring

The presence of life in ballast water can be determined quickly by several techniques that assess bioactivity in the water. These techniques, many of which can now be automated, include measuring one or more of the following:

- Photosynthetic pigment. The amount of chlorophyll present in the water reflects the biomass of living phytoplankton in the water.
- ATP. The presence of a biochemical energy system, adenosine triphosphate, indicates that living cells are present.
- Nutrients. The amount of a compound such as nitrate or phosphate in the water indicates that level of nutrients available to support phytoplankton.

Another technique is to determine the presence and abundance of one or more particular species (such as a bacterium or dinoflagellate) known as indicator species. The potential presence of additional, similar species can then be inferred without actually undertaking a more extensive biological analysis. This indicator species approach is used in waste-water treatment, where certain organisms (e.g., enteric bacteria) are used as surrogates to predict the presence of pathogens in waste water, including bacteria, viruses, protozoans, nematodes, and flatworms.

Although the indicator species approach may not be useful for monitoring ballast water in all cases, it may be useful in specific instances. For instance, if ballast water had been taken up in an area known to harbor an unwanted species, that particular species might be searched for specifically. Particularly resistant forms known to present high risks (such as dinoflagellate cysts) might be selected for monitoring. At the same time, it could be assumed that, if a particular species were killed or removed, most other species would also be eliminated.

Level III Monitoring

Advanced biological analysis comprises collecting plankton samples from the water column and benthic samples from bottom sediment (if present), followed by taxonomic identification to the species level, if possible. Identification may be manual or flow cytometry, molecular probes, or immunofluorescence may be used (see Appendix H).

Level III monitoring with existing technology is probably not feasible except when the risk of introduction is very high. In particular, the time needed for advanced biological analyses is not compatible with shipping schedules. However, the development of automated techniques, such as immunofluorescence, may eventually allow onboard identification of specific taxonomic groups. A number of biochemical methods for monitoring water are currently under development and might be applicable to level II and level III monitoring in the longer term (see Appendix H).

MONITORING AFTER TREATMENT OF BALLAST WATER

In contrast to the generic approaches to ballast water monitoring described above, monitoring methods after ballast water has been treated on board may be closely tied to the method used to treat the ballast water. For example, it may be possible to monitor the effectiveness of biocide treatments by monitoring the presence and concentrations of residuals in ballast water.

Australian researchers have identified three steps needed when monitoring the treatment of ballast water on board ships (AQIS, 1993):

- Record equipment operation to confirm that all ballast water has been appropriately treated.
- Sample treated ballast water and sediment to check performance of the equipment.

- Perform random inspections of facilities to ensure that they are properly maintained and operated.

The present discussion focuses on the second step for the three most promising treatment categories identified in Chapter 4—biocidal (chemical) treatments, filtration (mechanical) systems, and thermal (physical) treatments.

The effectiveness of treating ballast water with a chemical biocide could be monitored by measuring the amount of biocide (residual) in the water, rather than the organisms. For example, in wastewater disinfection, where chlorine is the most common biocide, the residual levels of free chlorine are routinely measured by various colorimetric or titrimetric methods. Because of environmental concerns about chlorine, the U.S. Environmental Protection Agency (EPA) has placed limitations on the discharge of free residual chlorine. From an environmental point of view, a desirable ballast water biocide would be one that quickly degrades into nontoxic byproducts and does not pose a chemical threat to the receiving environment.[2] However, this could make monitoring for the residual biocide itself more complicated.

Monitoring for turbidity after filtration may be a reasonable technique to assure the effectiveness of the filtration process. Turbidity indicates that there are particles in the water, some of which may be living organisms.[3] Low turbidity would indicate a lack of dense biological populations. High turbidity could indicate concentrations of plankton and suspended sediment.

In the case of thermal treatment, the success of treatment would need to be measured in terms of the degree of completion of the inactivation process. In laboratory tests, the effect of heat treatment on toxic dinoflagellate cysts was determined by observing germination rates when culture medium was added to the treated sample (Bolch and Hallegraeff, 1993). Clearly such an approach—which is not applicable to all organisms—would not be practical for shipboard use, and development of a simple, onboard test method is needed to support the heat treatment option for treating ballast water. It would also be possible to monitor temperature versus treatment time as an indicator of effective treatment.

SAMPLING ISSUES

There are a number of sampling issues associated with using level II or level III monitoring to establish the presence of living organisms in ballast water. Certain species of plankton migrate vertically in the water column, going up at night and down during the day; this behavior may continue for several days in the absence of light cues. Further, ballast water samples taken during the day in

[2] A discussion of discharges to the environment following ballast water treatment is given in Chapter 4.

[3] The use of particle size analysis as a monitoring tool may merit consideration in some situations.

cargo holds whose hatch covers have been opened (and thus the water fully exposed to daylight) may not reveal planktonic species that have descended to the tank bottom. Alternatively, ballast tanks that are suddenly exposed to a light source (for example by removing a deck manhole cover on a topside tank) may cause certain species to be attracted to the light, and their density may be artificially increased. When feasible, ballast water should be sampled at various depths and as deep as possible, and inline sampling should be used when filling ballast tanks, if possible.

MONITORING SEDIMENT

Ballast sediment at tank and hold bottoms requires periodic monitoring to understand its influence on turbidity readings and nutrient levels and its potential to act as a sink and source of transported organisms. Four methods are available for sediment sampling and monitoring (AQIS, 1992):

- In-line turbidity meter. The turbidity of outflow water (whose turbidity has been premeasured at different vertical levels in the tank) could be measured. Comparing elevated turbidity readings of outflow water with turbidity readings of the tank's water column could indicate input from bottom sediment. However, a determination that sediment is being discharged comes too late to permit remedial action. Monitoring the turbidity of incoming ballast water forewarns the ship's master that sediment is present and that changing or treating ballast water will probably be required prior to arrival at port and deballasting.
- Suspended sediment sampling at ballast load port. Representative sediment samples could be taken by lowering sampling devices through deck-level access openings. This method could be used to obtain water column samples during or just after ballasting, when the bottom sediment is still suspended in the water column and has not settled to the bottom of the tank.
- Direct observation and sampling via tank access. Tank bottoms are typically inspected for their sediment loads by entering an empty tank and examining the amount of sediment present. Again, a determination that sediment is present comes too late to permit remedial action to control the discharge of suspended sediment in the ballast water.
- Sediment sampling at ballast load port. Samples of harbor-bottom sediment could be taken at the ballast water loading port adjacent to the cargo discharge berths as an indicator of the sediment content of ballast water.

If either of the last two methods were used, sediment samples could be taken to determine the presence of living organisms, such as dinoflagellate cysts and benthic invertebrates.

SETTING STANDARDS

Cost-effective implementation of the monitoring approaches described in this chapter requires (1) the development of monitoring technologies with the necessary sensitivity and (2) the determination of appropriate standards. As noted in Chapter 3, identifying risk-based levels of protection—and developing associated standards—depends on both biological data (assessing the probability of establishment) and social judgements regarding potential risks (assessing the consequences of establishment) (see Box 3-3). Assessment of the consequences of introductions of nonindigenous aquatic species is beyond the scope of the present study. However, the committee considered some brief remarks on the challenges of setting standards to be appropriate in the context of the preceding discussion of monitoring. The ability of biological science to predict the probability of establishment of nonindigenous aquatic species is currently very limited. As noted earlier, it is not known how many individuals of a given species, or their densities, are needed to establish a viable, self-reproducing population at a new site. Even if this number were known, it would not be consistent from one receiving environment to another. It is daunting to contemplate the amount of research that would be required to adequately assess all of the organisms that could possibly be established in new locations.

The use of risk assessment to establish safe levels of exposure to carcinogens and other toxic chemicals provides an interesting analogy. In setting such standards, two different approaches are used. In one approach, toxicological data on individual chemicals are used to estimate the dose of a carcinogen that would result in a one-in-a-million risk of cancer. While limited, these toxicological data are generally far more extensive than current information on how many individuals need to be released in a new environment to establish a viable population of a given species. Alternatively, standards for controlling water pollution are sometimes based on levels of contaminants that can be achieved after treating water with the "best available technology." It remains to be seen to what extent such approaches can be used in setting standards for discharge of ballast water.

Regardless of how standards for the safe release of ballast water are determined, it is important that the supporting reasons and assumptions be fully transparent to all those affected. In addition, the implementation of ballast water controls based on the standards should be accompanied by appropriate outreach, education and training activities.

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6

Conclusions and Recommendations

Reports of marine and freshwater invasions of nonindigenous species are increasing as human activities continue to disperse organisms at a significant rate. There are many vectors for transferring species to new environments, either intentionally or unintentionally. A significant known pathway for species introduction is through ships' ballast water, the use of which is necessary for safe ship operations. The committee reviewed the state of practice of the prevention and control of nonindigenous species introduction in ships' ballast operations, and assessed potential alternative control strategies and management options for biological efficacy and practicability and for their impacts on ship and crew safety and on the environment. The committee's conclusions and recommendations are provided below.

CONCLUSIONS

Conclusion 1. No system or practice in use today will totally prevent the introduction of unwanted nonindigenous aquatic species into port or estuarine waters. Also, there are no off-the-shelf technologies specifically designed for treating ballast water that are suitable for use on board ship without some redesign and modification.

Conclusion 2. The IMO has developed and circulated a set of voluntary guidelines that are in use today. These guidelines are aimed at minimizing the introduction of unwanted aquatic organisms into the marine environment through their transport in ships' ballast water. Currently, the best option for minimizing such introductions is deballasting and reballasting a ship in mid-ocean areas. The

United States requires the use of this technique for ships destined for the Great Lakes and upper Hudson River. Continuous flushing of ballast tanks is thought to be an acceptable alternative technique for changing ballast water at sea. However, neither of the options for changing ballast water is suitable for all ships or all trade routes under all circumstances.

Conclusion 3. A ballast water operations plan, developed in conjunction with the ship cargo plan for each voyage, would provide flexibility in managing ballast water. Such a plan would take account of available information on locations and times when ballast is likely to contain unwanted organisms.

Conclusion 4. The member states of IMO are currently drafting a proposed new annex to MARPOL 73/78. Essentially, this annex would make mandatory the use of the existing voluntary guidelines. A new annex to MARPOL 73/78 probably would not be in force before the turn of the century. In the meantime, some countries already are establishing unilateral regulations for the control of ballast water introductions. Such unilateral controls could have significant negative consequences for ships in worldwide trade.

Conclusion 5. Developing regulations to control ballast water operations will be most effective at the international level. Without a governing international framework, and considering the diversity of vessels, trade routes, and ecosystems, controls tailored to local circumstances could lead to a patchwork of national (and state) regulations and resulting difficulties in compliance. The scientific and technical basis for ballast water regulations needs to be updated continuously to take advantage of R&D in the United States and other countries that leads to a better understanding of the problem of aquatic nuisance species and improved technologies for controlling ballast water.

Conclusion 6. Early involvement of all interested parties is important to the successful development and implementation of guidelines and regulations for the control of ballast water. The problem of nonindigenous species transfer has implications for society as a whole and is not simply an issue for the shipping industry.

Conclusion 7. Onboard systems for treating ballast water would give ships the most flexibility for managing ballast water, although port-based systems may offer some advantages. Experience with land-based waste water treatment systems is a useful starting point for assessing candidate technologies for treating ballast water on board ships. However, the operational constraints associated with shipboard use, including the high flow rates associated with pumping ballast water and the presence of sediment, impose additional demands on candidate systems.

Conclusion 8. The most promising technologies for successfully treating ballast water on board ships appear to be physical separation techniques. Filtration could remove all materials, down to a predetermined size, during uptake, thus removing many unwanted organisms from ballast water. Using filtration is applicable to most ships, regardless of the characteristics of the water being taken up for ballast. Continuous backwash filtration is the most favorable candidate technology for use on board ships based on environmental, health, safety, effectiveness, and cost considerations. The size of current media filtration systems precludes their use on board ship, but their performance and design could be optimized for compatibility with ships' operations, for example, by reducing their size and providing the capability to handle high flow rates.

Conclusion 9. Chemical and thermal technologies are potenially acceptable alternatives to filtration for treating ballast water on board ships. Further investigation is needed to establish, with more confidence, the relationship between biocidal dose or temperature and the time needed to kill or inactivate unwanted organisms. Development work is also required to optimize system designs for shipboard implementation.

Conclusion 10. Some emerging electro-treatment technologies have shown encouraging results in laboratory tests. However, all technologies investigated—aside from filtration, chemical and thermal treatments—appear to have major limitations and, therefore, require extensive development for possible onboard application. The transition from laboratory scale to shipboard systems carries high technical risk, and development may be extremely costly.

Conclusion 11. Ultraviolet, acoustic, magnetic, and oxygen-deprivation technologies for treating water have been successful in selected land-based applications, but these technologies have not demonstrated their effectiveness in treating a wide range of aquatic species, especially on board ships. Therefore, they are not considered to be prime candidates for treating ballast on board ships when they are used alone.

Conclusion 12. Certain treatment approaches would cause byproducts or residuals to be discharged overboard. As a general practice, discharges to the environment (e.g., chemicals filtrates, heated water) resulting from treating ballast water should be minimized. The trade-offs between the risk of introducing nonindigenous aquatic nuisance species and the risk of releasing small quantities of residuals produced from treating ballast water require further evaluation.

Conclusion 13. Questions remain regarding appropriate levels of risk of introducing unwanted organisms: What level of reduction of biological activity is necessary? What standard can be used to declare that a particular treatment has been effective? How clean is clean? Better databases on the biology of aquatic organisms would help address these questions by providing more extensive data for risk assessments. Meanwhile, probabilistic risk analysis based on limited available data can be a useful indicator of cost-effective management strategies.

Conclusion 14. The implementation of methods for managing ballast water will require the development of practical measures for verifying compliance and assessing accountability and responsibility; therefore, automated monitoring and the required record keeping are desirable so that crew members and regulating authorities can readily and effectively ensure that agreed-upon standards have been met. If individual species have been identified, thereby raising concerns about ballast water discharge, monitoring procedures for source water and ship-held water need to be established to determine whether or not treatment is necessary. It is essential that any treatment be monitored for effectiveness using automated procedures that require little crew intervention, other than noting whether or not standards have been met.

Conclusion 15. Turbidity may currently be the most effective indirect indicator of the possible presence of living organisms in ballast water. Basic water-quality parameters can be monitored by automatic inline equipment that provides continuous readouts for subsequent computer storage or direct transmission to shore.

Conclusion 16. One proposed approach to monitoring shipboard management practices involves a "sampling and dispatch" method. Chronic carriers of known unwanted aquatic species would be required to air freight samples of their ballast water to authorities at the destination port for testing. When the results are known, the ship would be instructed whether or not some form of treatment is required in transit. Such an approach would require careful sampling of ballast water and the establishment of appropriate test facilities.

Conclusion 17. It would be helpful in identifying possible introductions if each port were to develop a monitoring program based on internationally agreed-to standards to establish an ongoing database of organisms present in its waters.

RECOMMENDATIONS

Recommendation for the U.S. Coast Guard. Managing the unintentional introduction of nonindigenous organisms into U.S. waters through ballast water should follow two parallel courses:

- Support current international activities conducted under the auspices of IMO.
- Introduce national voluntary guidelines aimed at minimizing the risk of

introductions until such time as mandatory international standards can be developed. These guidelines should require a plan for ballast water loading and discharge, developed in conjunction with the cargo plan for each voyage.

Recommendation for the Aquatic Nuisance Species Task Force. The following actions should be taken as part of the cooperative national program to prevent unintentional introductions of nonindigenous organisms through ballast water:

- The United States should support and encourage the early elaboration of a new annex to MARPOL 73/78 making mandatory the use of the existing voluntary guidelines; meanwhile, the IMO-sponsored voluntary guidelines should be continuously reviewed and updated.
- The cognizant U.S. authority,[1] as a matter of priority, should be tasked with developing domestic guidelines to minimize the translocation of unwanted nonindigenous organisms among U.S. ports by vessels engaged in trade along U.S. coasts. All interested parties should be involved from an early stage in formulating such guidelines and in developing ways to implement them.
- The associated U.S. authorities should sponsor and encourage further research and development for killing or removing aquatic organisms in ballast water. In this regard, options for treating ballast water should not be limited to technologies for shipboard use. Shoreside treatment should be investigated as a possible alternative.

Recommendation for the Aquatic Nuisance Species Task Force. National research and development, including one or more demonstration projects, should focus on the following:

- optimizing the filtration approach to treating ballast water
- identifying the level of biological activity that indicates that treatment has reduced the risk of species introduction to an acceptable level
- developing automated monitoring systems suitable for shipboard use

To avoid duplication of effort, these activities should take into account related research and development in other countries.

Recommendation to the Aquatic Nuisance Species Task Force. The results of this study should be disseminated to coastal states, including states bordering the Great Lakes.

Recommendation for the U.S. maritime industry. At the same time research and development are undertaken to address long-term solutions for controlling

[1] The cognizant U.S. authority may be the Coast Guard, the state, or the port authority, depending on circumstances.

introductions of nonindigenous aquatic organisms, the U.S. maritime industry should pursue implementation of a combination of practices for managing ballast water and the control options described herein, within the framework of existing international guidelines.

Recommendation for the member states of IMO. Future international considerations should include establishing guidelines for baseline sampling of ports for specific organisms. Samples should be tested to agreed-upon international standards to facilitate comparisons of the water of each ballast uptake port with the water of receiving ports.

Recommendation for the member states of IMO. In future discussions and updates of the existing voluntary guidelines (IMO Assembly Resolution A.774(18), 1993), further consideration should be given to the maintenance of appropriate ships' logs and records of ballast water movements and any management practices used. These data could be valuable when used in conjunction with measurements of basic water-quality parameters to verify that ballast water has been effectively managed.

APPENDICES

APPENDIX A

BIOGRAPHICAL SKETCHES OF COMMITTEE MEMBERS

Joel D. Sipes (chair), is a retired rear admiral of the U.S. Coast Guard. In that capacity, he managed all Coast Guard activities in the navigable waters in the northeast United States out to 200 miles. Prior to that posting, RADM Sipes served in Washington as chief, Office of Marine Safety, Security and Environmental Protection. In that position he was responsible for national programs involving design, construction, and inspection of commercial vessels; the safe transportation of oil and hazardous materials; licensing and certification of seamen; port safety and security; and marine pollution prevention and response activities. He also led the U.S. delegation to the International Maritime Organization. RADM Sipes received a B.A. in general engineering from the U.S. Coast Guard Academy and a Masters of Public Administration from the University of Rhode Island.

John W. Boylston is the president of Argent Marine Operations, Inc. He has an extensive background in naval architecture; he is responsible for refurbishment and return of liquefied natural gas vessels to be deployed for trade, has managed tanker design projects, and was responsible for the design and construction of 13 container ships and the conversion of 35 others. Mr. Boylston has worked on four National Research Council panels addressing human error in navigation, tank vessel design, research needs to prevent collisions, and replenishment of combat vessels by container ships. He is a member of the Society of Naval Architects and Marine Engineers and of the American Bureau of Shipping. He received a B.S. degree in marine transportation from the U.S. Merchant Marine Academy and a B.S.E. in naval architecture and marine engineering from the University of Michigan.

James T. Carlton is director of the Maritime Studies Program at Mystic Seaport and professor of marine sciences at Williams College. Dr. Carlton's research interests are in the ecology, biogeography, and dispersal mechanisms of introduced species in marine, estuarine, and freshwater environments and the effects of invasions on the structure of natural communities. He is the principal investigator for the National Biological Invasions Shipping Study, a study authorized in the 1990 Nonindigenous Aquatic Nuisance Prevention and Control Act. Dr. Carlton has served on several national and international committees. He is chair of the Working Group on Introductions and Transfers of Marine Organisms of the International Council for the Exploration of the Sea, co-chair of the Committee on Biological Diversity in Marine Systems of the National Research Council, and a member of the Australian Commonwealth Scientific and Industrial Research Organisation Advisory Panel on the introduction of marine pest species. Dr. Carlton received a B.A. from the University of California, Berkeley and a Ph.D. from the University of California, Davis.

Michael J. Fordham is former group vice president of CAST, an intermodal shipping company, where his responsibilities encompassed marine and container operations, commercial/chartering, bulk, conventional and passenger divisions, and group risk and asset management. Mr. Fordham's career began at BP Tanker Company, where his duties covered a wide range of tanker operations. Upon becoming master and coming ashore, his responsibilities expanded to include vessel operations and management. Involvement in several BP group projects followed, many of which resulted in International Maritime Organization ratification by member nations, including, at the concept stage, the now globally adopted crude oil washing system. Mr. Fordham is a master mariner and received a National Diploma in nautical science and a commission in Her Majesty's Royal Navy Reserve.

Michael G. Parsons is associate dean for undergraduate education and professor of naval architecture and marine engineering at the University of Michigan. He is responsible for introducing several new courses to the university curriculum, including Ship Power Systems and Introduction to Naval Architecture and Marine Engineering. His research focus is on ship design improvements for safety and operational aspects, and he has published numerous papers in this area. Dr. Parsons recently carried out a study for the National Oceanic and Atmospheric Administration on ship operational safety aspects of ballast exchange at sea. Prior to joining the faculty at the University of Michigan, he was employed as a fluid systems engineer for the U.S. Navy. Dr. Parsons is a member of several organizations, including the Society of Naval Architects and Marine Engineers, (past chair of the Great Lakes and Great Rivers section) and has served on the Council of Sea Grant Directors. He received a bachelors degree from the University of Michigan, a masters degree from the Catholic University of America, and a Ph.D. from Stanford University.

Ray Skelton is environmental and government affairs director and foreign trade zone manager for the Seaway Port Authority of Duluth, Minnesota. His responsibilities involve close contact with state and federal governments as well as maritime-related companies and associations. He currently represents Great Lakes ports on several committees, including the Voluntary Ballast Control Committee, the American Association of Port Authorities' Harbors, Navigation and Environment Committee, and the U.S. Fish and Wildlife Ruffe Task Force. He is also president of the U.S. Propeller Club Duluth-Superior Chapter. Captain Skelton received a first class pilot's license in 1972 and a master's license in 1976 from the Associated Maritime Officers School of Navigation.

Alan H. Taylor is environmental and crisis systems manager with BHP Transport, located in Melbourne, Australia, where he is in charge of risk management, crisis and emergency management, and all environmental matters of BHP's international transport business. Mr. Taylor has been actively involved in ballast water technology research through the Australian Quarantine Inspection Services' Ballast Water Management and Scientific Committees and the International Maritime Organization's Ballast Water Working Group. Prior work includes appointments as technical manager of ALSOC Pty Ltd., where he led teams in the technical development of seven liquefied natural gas carriers, and as engineer and technical superintendent and assistant to operations manager for Jardine Mathesons Company, Ltd., in Hong Kong. Mr. Taylor is a fellow of the Institute of Marine Engineers, a member of the Royal Institution of Naval Architects, and a chartered engineer registered with the Engineering Council (United Kingdom).

E. Dail Thomas II is head of the Environmental Effects Branch, Materials Science and Technology Division at the Naval Research Laboratory in Washington, D.C. His work with the Navy is concentrated in the areas of biofouling control, corrosion engineering, and heavy metal discharge. Prior to this appointment, he headed the corrosion engineering staff at the Naval Research Laboratory in Key West, Florida. Mr. Thomas has conducted studies of engineering alloy heat transfer losses due to biofouling and has developed dockside and shipboard systems, including hypobromite generators and monitors/sensors, to control biofouling accumulation in seawater cooling systems. He received a B.S. degree from the University of Maryland and an M.S. degree from the University of Delaware.

Thomas D. Waite is associate dean for research and graduate studies and professor of environmental engineering at the University of Miami in Florida. He also serves as director of the Laboratories for Pollution Control Technologies at the university. His research includes disinfection of waste water effluents and sludge and the use of innovative and new treatments for remediation of hazardous wastes. Dr. Waite has also served as research engineer at the David Taylor Naval Ship R&D Center. During his tenure, his work focused on application of technologies for treatment of oily bilge water in vessels. Other achievements include development of the academic program for environmental engineering at the University of Miami. Dr. Waite received both bachelors and masters degrees from Northeastern University and a Ph.D. from Harvard University. He is a registered professional engineer with the state of Florida.

Judith S. Weis is professor of biological sciences at Rutgers University. Dr. Weis' research area is the responses of estuarine organisms to stresses, including contaminants, and she has published extensively on that subject. Dr. Weis has served as associate dean for academic affairs at the university and as developer and coordinator of the Science, Technology, and Society Program between Rutgers and the New Jersey Institute of Technology. A fellow of the American Association for the Advancement of Science, she served as congressional science fellow for the U.S. Senate Environment and Public Works Committee, where she worked on several legislative initiatives to control toxic substances and protect drinking water. Recently, she was a visiting scientist at the Environmental Protection Agency (EPA), and she has provided expertise to the EPA and National Oceanic and Atmospheric Administration on marine pollution, in addition to serving as a board member of the American Institute of Biological Sciences and the Society of Environmental Toxicology and Chemistry. She is a former member of the Marine Board. Dr. Weis received a B.A. Degree from Cornell University and M.S. and Ph.d. degrees from New York University.

APPENDIX B

Committee Meetings and Activities

First Committee Meeting, October 25–26, 1994, Washington, D.C.

The following presentations were made to the committee:

Aquatic Nuisance Species Task Force/International Maritime

Organization Interest in Study.

Commander Richard Gaudiosi, U.S. Coast Guard

U.S. Research on the Role of Vessels in Nonndigenous Species

Introduction and Control.

James Carlton, Williams College

Nonindigenous Species Research at the Smithsonian Environmental

Research Center.

Greg Ruiz, Smithsonian Environmental Research Center

SHIPS' BALLASTING REQUIREMENTS AND SYSTEMS:

General Cargo Vessels

Captain Joseph Delehant, Sea Land (retired)

Oil Tankers

Captain James Morgan, ARCO

Bulk Ocean Shipping

Jeffrey Flumignan, Liberty Maritime

Great Lakes Shipping

Richard Harkins, Lake Carriers Association

Second Committee Meeting, February 7–9, 1995. Irvine, California

The following presentation was made to the committee:

The Proposed Nonindigenous Aquatic Organisms Risk Analysis Review Process.

Richard Orr, U.S. Department of Agriculture, Animal and Plant Health inspection service

At the Port of Long Beach the committee toured *The Patriot*, a Sea Land container vessel, with Captain Kim Davis and Captain Joseph Delehant, and the ARCO tanker *Prudhoe Bay* with Captain Jim Morgan. On *The Patriot* a mud sample from Yokohama, brought on board by the anchor, was taken.

Writing Group Meeting, April 1–3, 1995, Washington, D.C.

Third Committee Meeting, May 15–17, 1995, Duluth, Minnesota

Ballast Water Treatment Technologies Workshop, Part 1

The following presentations were made to the committee: Ozone Treatment.

Michael Walsh, Alten Water Treatment Corporation, Palo Alto, California

Electric Pulse Treatment

Thomas Fox, Center for Advanced Ship Repair and Maintenance, Norfolk, Virginia

Metal Ion Treatment.

John Hayes, Pan-Ionic Ltd., TP Technology plc, High Wycombe, Buckinghamshire, England

Magnetic Water Treatment.

Charles Sanderson, ZMT Industries, Inc., Fort Wayne, Indiana

ET Formula #1 (Modified Bentonite Clay).

Stuart Forrest, E.T. Ventures, L.L.C., Johns Island, South Carolina

The committee took a boat tour of Duluth Harbor to learn about the nonindigenous species problem and control strategies in the Great Lakes Basin.

Monitoring Task Group Meeting, July 17–18, 1995, Washington, D.C.

Implementing Change Task Group Meeting, July 20–22, 1995, Honolulu, Hawaii

Technology Task Group Meeting, August 22–24, 1995, Washington, D.C.

Ballast Water Treatment Technologies Workshop, Part 2

The following presentations were made to the committee:

Acoustic Solutions to Environmental Problems.

Mark Kenna, Sonalysts, Inc.

Multi-media Filtration Systems.

Thomas Waite, University of Miami

Immediate Research Priorities for Improvement of Ballast Water Control.

Eric Reeves, U.S. Coast Guard, Chief, Port and Environmental Safety Branch, Ninth Coast Guard District, Cleveland, Ohio

Fourth Committee Meeting, October 2–4, 1995, Washington, D.C.

The following presentation was made to the committee:

Application of Information-Limited Risk Analysis to the Aquatic

Nonindigenous Species Question.

James Englehardt, University of Miami

Fifth Committee Meeting, January 18–20, 1996, Irvine, California

Selected members of the committee attended the following meetings and symposia:

International Maritime Organization, Ballast Water Working Group, September 1995 and July 1996, London, England

First International Scientific Conference on Ballast Water, International Council for the Exploration of the Sea (ICES), 83rd Statutory Meeting, September 1995, Aalborg, Denmark

APPENDIX C

Explanation of Basic Stability

A ship or any other freely floating body displaces its own weight of the liquid it is in when afloat. This weight (w) acts downward through the center of gravity of the body (G) and is resisted by an upward buoyant force (equal to w), which acts through the center of buoyancy (B) (see Figure C-1). (B) is the geometric center of the submerged volume displaced by the ship. The metacenter (M) is the point through which all vertical forces are said to act.

The actual "all up weight" of a ship and its contents is equal to the weight of water displaced by the hull; accordingly, this is referred to as its displacement. A vessel's displacement varies over a range of conditions from extreme lightship to a deep, heavy-loaded condition. The displacement alters as cargo or ballast is loaded or discharged or as fuel is consumed.

In stable ship, the centers of buoyancy and gravity strive at all times to remain vertically aligned. When a stable ship is caused to heel by an external force, such as wind, wave, or turning motion (not weight shift), the consequent change in underwater hull shape will result in (B) moving to one side while (G) does not move. The horizontal separation of (B) and (G) so caused is referred to as the righting lever, GZ (see Figure C-1), and the resulting righting moment, (w x GZ), will cause the vessel to oscillate from side to side as it attempts to realign (B) and (G).

The measure of a ship's initial stability, when upright or nearly upright, is indicated by the height of the metacenter (M) above (G), which is referred to as the metacenter height, GM, while the horizontal distance, GZ, more accurately indicates the measure of stability at angles of heel (OB:FO: "Theta") in excess of 5 degrees from the vertical. GZ is referred to as the measured of static stability.

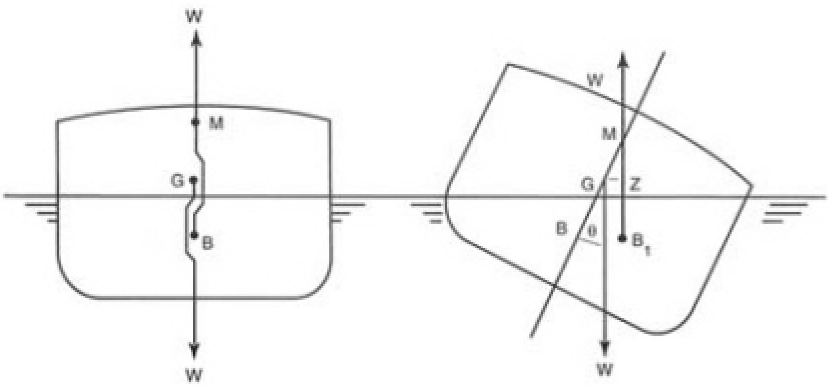

FIGURE C-1 Righting lever.

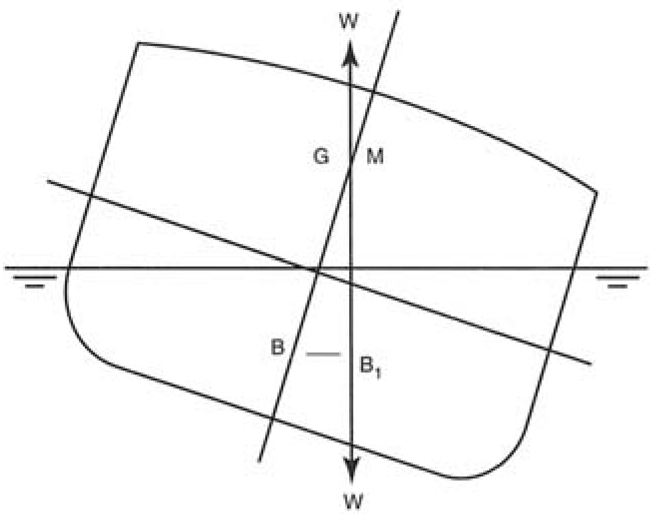

FIGURE C-2 Zero GM.

Should the ship's center of gravity (G) coincide with (M) and an external force be applied, the ship will assume an "angle of loll." The ship will maintain the assumed angle until a further force is applied. Should another external force be applied, the ship may assume an angle of loll to the other side or may worsen the existing loll condition if there is no righting lever, GZ, to correct the assumed heel angle. In this condition the ship is said to have zero or no GM (see Figure C-2).

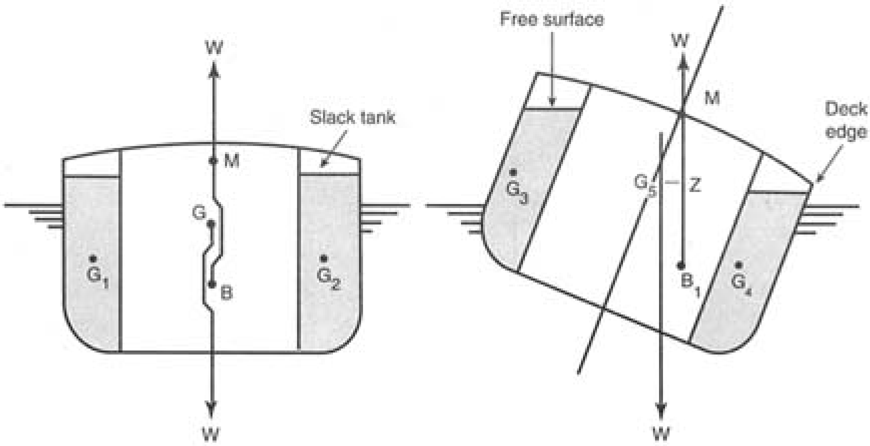

FIGURE C-3 Reduced GM with slack tanks (free surface effect).

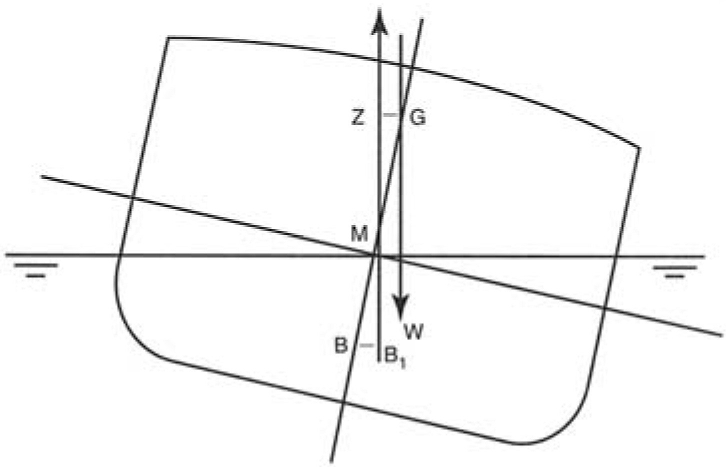

FIGURE C-4 Negative GM.

As shown in Figure C-1, when the vessel is upright, the center of buoyancy, (B), and the center of gravity of the ship, (G), remain in line and the ship is transversely stable, even with slack; that is, even with the ballast tanks partially full. However, if an external force is applied (because of wind, wave action, or the ship turning) and the ship is caused to heel, the center of gravity of the water in the ballast tanks (G_1) and (G_2) will move to positions (G_3) and (G^4), resulting in the center of gravity of the ship moving from (G) to (G_5) (see Figure C-3). This movement reduces the original righting lever, GZ, and the resultant height of the ship's GM. The ship therefore becomes less transversely stable.

Should the ship, for whatever reason, continue to heel, the position of (G_5) will continue to move due to the movement of the center of gravity of the affected ballast tanks, thereby reducing the vessel's GM and the resulting GZ. If the deck edge becomes immersed, the center of buoyancy (B) will move inboard, the effect of which will again reduce GM and the resultant righting moment, GZ. The effect of this change will make the vessel become very "tender," and it will "flop" from side to side.

If more tanks are made slack or there is a cargo shift due to the excessive angle of heel, it is possible for (B) and (G_5) to reverse positions. Should this occur, GZ will be converted from a righting lever into a coupled turning force, which could cause the ship to capsize. This condition is known as negative GM (see Figure C-4).

APPENDIX D

Alternative Ship Designs

Ship owners and operators want to carry as little ballast as possible on a voyage. Increased ballast causes a reduction in ship speed and an increase in fuel consumption, or both, with associated increases in costs. Revenue is based on cargo, not ballast, so design modifications that reduce the need for ballast without compromising safety are potentially beneficial to owners and operators. When new ships are constructed or major alterations are made to existing vessels, opportunities may exist to (1) limit total ballast water requirements, (2) improve the safety of at-sea ballast water change, and (3) incorporate structural and piping designs that trap less sediment and are easier to clean.

LIMITING BALLAST

New ships could be designed that would eliminate the normal ballast loading and discharging operation by reducing the cargo capacity and incorporating permanent, retained ballast within the deadweight of the vessel. However, taking one-third to two-thirds of a vessel's load capacity (deadweight) for non-earning "cargo" (i.e., ballast) would have dire commercial consequences and would not be a viable option for ship owners. The resulting shortages in worldwide shipping capacity would have a dire impact on world trade. The shipbuilding capacity to replace or increase current shipping capacity is not available. Nor are trained crews available to staff many new ships.

If it were possible to maintain ships fully loaded with cargo at sea on all legs of a voyage, thereby avoiding the ballast leg, ballast water would only need to be taken on board temporarily in port as cargo was discharged. Later, when new cargo was loaded, in the same port, the temporary ballast water could be discharged into the same environment from whence it came. Although this is an extremely attractive scenario from a commercial perspective (full ships at all times), this approach to controlling introductions of nonindigenous species through ballast operations would be difficult to implement in practice because of different cargo requirements, the geographic separation of loading and distribution points, and the imbalance of trade.

Under certain circumstances many types of ships—some container vessels, for example—can retain ballast water on board by moving it within the ship's ballast system to compensate for cargo deployments that affect vessel trim and stability.

IMPROVING BALLAST CHANGE

Currently, one of the best available options for controlling ballast water is changing it in open ocean by deballasting and reballasting. A new ship design with increased structural strength and stability would make at-sea ballast change safer. This option would require that the proposed plans for changing ballast water be approved by the vessel's classification society and the regulatory authority of the flag state.

If the strength or stability of a vessel cannot sustain complete discharge and refilling of ballast tanks at sea, the continuous flushing method for changing ballast water change could be used. Some typical design modifications that could be used are as follows:

- Tanker-type hatches could be fitted to the weather deck in way of the topside tanks, and the topside could be interconnected with the lower wing tanks. This modification would be suitable for bulk carriers.
- This design would be the same as above, but instead of fitting tanker hatches, larger ventilation pipes would be fitted with cross-sectional areas capable of handling flows equal to the largest ballast water pumping capacity.

CLEANER BALLAST TANKS

To assist in the complete removal of ballast water and sediment, the internal features of the ballast system structure could be designed to facilitate draining of ballast water to the ballast suction and stripping suctions. Horizontal, flat longitudinal surfaces could be fitted with drain holes located along their length and adjacent to vertical surfaces. Alternatively, horizontal surfaces could be designed to shed water or sediment by slight angling downwards, with the return angles or face angles fitted to the underside of the longitudinals. Smooth tank coatings would also reduce clingage and allow for better discharge of ballast sediment.

For vessels that carry small quantities of ballast water in relation to their size, the double-bottom or side tanks could be fitted with additional divisional bulkheads. On a designated voyage between scheduled ports, the ballast water loaded in a port might be able to be held on board and discharged again at its origin. If ballast water loading were necessary in one port, the ballast could be retained on board until the next visit to that port. However, the inventory control requirements of such an operation, coupled with unpredictable cargo and weather-related ballast requirements, would probably render this approach impractical in most cases.

APPENDIX E

Great Lakes Maritime Industry Voluntary Ballast Water Management Plan for the Control of Ruffe in Lake Superior Ports, 1993

GREAT LAKES MARITIME INDUSTRY
VOLUNTARY BALLAST WATER MANAGEMENT PLAN
FOR THE CONTROL OF RUFFE IN LAKE SUPERIOR PORTS
1993

Owners and operators of vessels in the domestic and international trade on the Great Lakes recognize their role in assisting the governments of the United States and Canada in controlling the introduction and spread of non-indigenous fish species. We recognize that control must be on many fronts, including ballast water management, chemical control, predatory fish control, and other mechanisms. Vessels must use ballast water for safety purposes to provide adequate stability, trim, propulsion, maneuverability, and hull stress control. Recognizing these constraints, the marine industry will do everything within its power, consistent with safety and stability, to decrease the spread of known unwanted non-indigenous species. The introduction of new species from outside the system is under the control of the U. S. and Canadian Coast Guards through ballast water exchange regulations prior to entry into the system. This plan deals with the control of the spread of the European Ruffe from Western Lake Superior ports, in particular, Duluth/Superior or other harbors where Ruffe colonies are documented.

FOR VESSELS DEPARTING LAKE SUPERIOR PORTS *WEST* OF BALLAST DEMARCATION LINE:

1) Operators of vessels pumping ballast water onboard in the above harbors, with ballast line intakes equipped with screens fitted with holes larger than ½" in diameter, are restricted at all times of the year in their pumping out of ballast water from these harbors into the Great Lakes or their Connecting Channels or harbors. This ballast water should be pumped out west of a ballast demarcation line between Ontonagon, Michigan and Grand Portage, Minnesota. Ballast water from these harbors must not be pumped out within 5 miles of the south shore of Lake Superior while west of the ballast demarcation line. Ballast exchange should take place in water at least 20 fathoms (120 feet) deep.

2) Operators of vessels pumping ballast water onboard in the above harbors, with ballast line intakes equipped with screens fitted with holes ½" in diameter or less, are restricted only during the period between May 15 and September 15 in their pumping out of ballast water from these harbors into the Great Lakes or their Connecting Channels or harbors. During this 4-month period, these vessels should pump out the harbor ballast water west of a ballast demarcation line between Ontonagon, Michigan and Grand Portage, Minnesota. Harbor ballast water must not be pumped out within 5 miles of the south shore of Lake Superior while west of the ballast demarcation line. Ballast exchange should take place in water at least 20 fathoms (120 feet) deep.

3) If ballast exchange is not completed at the time the vessel reaches the demarcation line, exchange may continue in Lake Superior, but only in waters at least 40 fathoms (240 feet deep) and 15 miles from shore. In all cases, exchange must stop before proceeding east of 86° west.

FOR VESSELS DEPARTING LAKE SUPERIOR PORTS *EAST* OF BALLAST DEMARCATION LINE:

4) Vessels departing Thunder Bay should limit pumping ballast onboard as in paragraphs 1) and 2) above. These vessels may exchange ballast in Lake Superior, but only in waters at least 40 fathoms (240 feet deep) and 15 miles from shore. In all cases, exchange must stop before proceeding east of 86° west.

FOR *ALL* VESSELS DEPARTING LAKE SUPERIOR PORTS:

5) Operators of vessels pumping in ballast water from the above harbors and leaving the harbor with that water will maintain a record showing the amount of ballast water taken, the means of control, if any, and the location where the treated or untreated harbor ballast water was pumped out.

6) The ballast water records will be available for review by U.S. or Canadian Coast Guard personnel.

7) The above requirements will be waived for vessels which attest by means of a log entry that the harbor ballast water from the above harbors will not be pumped out within the Great Lakes/St. Lawrence Seaway System (at least until reaching salt water). Masters of these vessels recognize that ballast water from the above harbors must not be pumped out in any other fresh or brackish water port and thus should exchange ballast with salt water.

VOLUNTARY BALLAST WATER MANAGEMENT PLAN CO-SPONSORED BY:

• Canadian Shipowners Association	• The Thunder Commission	• Shipping Federation of Canada
• Lake Carriers' Association 04/02/93	• Seaway Port Authority of Duluth	• U.S. Great Lakes Shipping Association

APPENDIX F

Candidate Shipboard Treatment Technologies: Supplementary Information

The supplementary information on thermal, electric pulse/pulse plasma, and acoustic technologies provided in this appendix is based primarily on data presented to the committee by equipment suppliers, technology developers, and research organizations. The information draws extensively on the responses to the treatment options query (see Appendix G).

THERMAL TREATMENT

High temperatures are commonly used to sterilize water in a wide variety of applications. The use of heat treatment to kill potentially harmful marine organisms in ships' ballast water is currently under investigation. Most research to date has been conducted in Australia, where the focus is on killing toxic dinoflagellates.

In the course of ballast water change trials on the 147,000-metric-ton bulk-ore carrier, *Iron Whyalla*, it was observed that the saltwater overboard discharge from the main engine coolers was sterile. Subsequent laboratory tests showed that dinoflagellate cysts of *Gymnodinium catenatum* are destroyed when exposed to temperatures of 45°C for a few minutes. The latest laboratory research indicates that exposure to temperatures of 35°C for approximately 12 hours may be sufficient to kill dinoflagellates. Controlled shipboard experiments were conducted on the Japanese vessel, *Ondo Maru*, to determine whether the water in ballast tanks may be sterilized over a long sea voyage by continuous flushing with ocean water heated to approximately 35°C. However, the test results were not conclusive.

Thermal treatment has also been investigated in the course of research directed toward finding methods for environmentally sound control of zebra mussels.

Available data suggest that heating water to the acute upper lethal temperature of zebra mussels (typically in the range 38°C to 43°C depending on the acclimation temperature), followed by a rapid return to normal temperatures, is a promising mitigation technique for zebra mussel fouling.

Heat treatment of ballast water is potentially attractive because (1) waste heat from the ship's engine is a possible energy source for heating ballast water, and (2) no chemical byproducts or residuals are discharged. Shipboard implementation of thermal treatment would only require additional pipework and possibly an additional pump, starter, and electrical wiring to allow the hot water to be pumped through the ballast tanks using the flow-through method. As discussed in Chapter 4, a number of critical factors will probably limit the use of thermal treatment to certain vessels on specific trade routes. These factors include voyage time, the volume of ballast water to be treated, the ambient water temperature, and specificity to target organisms.

Safety

There would be no special safety requirements since the equipment needed is standard shipboard kit.

Effectiveness

Higher organisms such as fish are more easily killed by thermal treatment than microbes. Current work focuses on destroying toxic dinoflagellates, and studies will be needed to determine the effectiveness of heat treatment in killing other specific target organisms. An advantage of the proposed flushing method is that the proportion of original sediment in the ballast tanks is reduced, thereby enhancing the overall effectiveness of the treatment.

Status of Technology

Heat treatment is a well-known technology for land-based applications, but its use on board ship is at a research stage with the aforementioned *Ondo Maru* trials. Shipboard implementation will require the installation of a suitable marine system and definition of treatment parameters (temperature and time) to establish the success of thermal treatment in sea-going conditions.

Power

The possibility of using various shipboard waste heat sources has been considered for the case of the bulk ore carrier, *Iron Whyalla*.[1] There are a number of

[1] Other ships operate under different conditions that would need to be evaluated in a broader assessment thermal treatment. Key factors are the availability of waste heat and options for water heating (heating during ballasting or deballasting, heating by circulation during the voyage, or flushing hot sea water through the ballast tanks).

possible options for using the 5.7 MW power potentially available from the main engine cooling circuits. Heating the ballast water on a once-through basis during ballasting or deballasting is not practical from an energy standpoint. Further, the main engine is not normally operating during these ballasting operations. Recirculation of ballast water during a voyage requires much less power, although temperatures would be limited, possibly to less than 40°C. Heating of the water in the ballast tanks by continuous flushing with heated ocean water is potentially the most attractive option for the *Iron Whyalla*, particularly if the "lower temperature, longer time" treatment proves effective. Energy consumption would be continuous to maintain the temperature of the ballast water at the required level for the necessary time.

Byproducts

Although thermal treatment does not involve the discharge of chemical byproducts and residuals, the release of heated water from ballast tanks may be of environmental concern (see Chapter 4). In addition, it may be necessary to filter out dead organisms following treatment.

Costs

The cost of additional pipework and pumps for a 147,000-metric-ton bulk carrier with about 60,000 metric tons of ballast water has been estimated at $50,000.[2]

Size, Complexity, and Maintenance

For the case cited above, the small additional pump needed could be readily accommodated on board ship. The complexity of the system would be standard for shipboard use. Maintenance requirements would be minimal.

Monitoring

A simple, shipboard test is needed to support the heat treatment option. It may be possible to monitor temperature versus time as an indicator of treatment effectiveness.

ELECTRIC PULSE AND PULSE PLASMA TECHNIQUES

Pulsed electric field technology is being investigated as a means of preventing biofouling of water intake pipes on ships and at shore-based facilities. Water is passed between two metal electrodes and subjected to an electric pulse on the

[2] All costs are given in U.S. Dollars.

order of one microsecond duration with 10 kV applied to the electrodes. Early laboratory tests have been designed to provide reproducible data showing the effect of pulse length, voltage, and water salinity on treatment effectiveness. Experiments to date have used brine shrimp *Artemia salina*, which can be either stunned or killed depending on the pulse voltage and duration. Other studies have shown submicrosecond electric pulses to be lethal to bacteria (*Escherichia coli*).

Pulse plasma technology is being evaluated for the treatment of sewage and other waste water. The method is based on existing pulse plasma discharge systems used in a variety of industrial applications, notably metal forming. Adaptation of the technology to water treatment involves delivering a high energy pulse to an in-water arc mechanism and generating a plasma arc in water. The pulse plasma arc discharge produces a short energy burst at very high power density across the electrode gap, generating an arc channel containing a highly ionized and pressurized plasma, which in turn transfers energy to the water via dissociation, excitation, and ionization; and a rapid temperature rise at the arc front. The discharge is an efficient method of promoting pyrolytic, hydroxyl radical, free electron and ultraviolet generated reactions in water. Additional destruction of biological material is likely to result from direct reaction of hydrated electrons due to the release of soft x-rays and high-energy ultraviolet radiation from the energized plasma. The intense cavitation events induced by shock waves may aid in the destruction of living organisms in the proximity of the arc discharge.

Safety

The high-voltage portion of an electric pulse treatment system can be encapsulated such that no high fields exist outside the treatment volume. As with any high-voltage device, hazards can be avoided with proper grounding and insulation.

Pulse plasma systems use pulse voltages on the order of 15 to 25 kV. In addition, the plasma produces electromagnetic radiation (ultraviolet and soft x-rays) and a high-pressure shock wave. Shielding, screening, and access panel interlocks would be required to ensure the safety of personnel.

Effectiveness

The ability of electric pulse treatment to kill a broad spectrum of species has not yet been demonstrated. For brine shrimp, 95 to 99.9 percent sterilization is claimed. The percentage sterilization may be increased by raising the energy per pulse (and associated power requirements).

Pulse plasma technology is reported to achieve 99.9 percent (or greater) sterilization. Increased treatment times (and power requirements) help assure that all life in the water is destroyed. The treatment is sensitive to the presence of sediment, although the performance degradation due to sediment is claimed to be less than for ultraviolet treatment.

Status of Technology

Electric pulse technology is at an experimental level. Work to date has been limited to laboratory tests and testing of a prototype system in a harbor. Scale-up may be an issue.

Pulse plasma technology for water treatment is at the exploratory development stage. Laboratory devices have been built, and the scientific validity of the method is under investigation. Although the plasma arc device is a mature technology, it is the committee's understanding that it is not used to any significant extent in the marine industry.

Power

The electrical energy needed to kill brine shrimp has been determined experimentally as 1 J/cm^3 for a pulse duration of 3 x 10^{-5} s. It is anticipated that such energy densities would be sufficient to kill any organism found in ballast water, with the exception of bacteria. For System A (see Chapter 4 and Appendix G), an electric pulse system providing approximately 600 kW average power would be needed.

Power consumption for a typical pulse plasma system is in the range 25 to 50 kW. Since the technology is currently only suitable for low flow rates, either multiple systems or recirculation would be required to handle typical ballast water treatment needs. Thus, power consumption could increase significantly.

Byproducts

Theoretically, pulses of electricity in salt water can generate chlorine electrolytically. However, no chlorine has been detected in electric pulse experiments conducted to date.

When in operation, pulse plasma systems vent gaseous decomposition products (primarily carbon dioxide). Sedimentation may be increased, depending on the marine life and compounds present in ballast water, and some filtration process may be needed to prevent degradation of treatment effectiveness. No toxic byproducts or residuals have been detected.

Costs

The capital cost of an electric pulse system for treating ballast water is estimated at $350,000, with a treatment cost of approximately $360 for a tank containing 25,000 m^3 of water.

Estimated costs for a pulse plasma treatment system are in the range $100,000 to $200,000, exclusive of installation. Operation and maintenance costs are estimated at around $150/hour, including electrode replacement but excluding the cost of electrical power. Ignitron replacement after 10,000 hours of operation would cost about $5,000.

Since both electric pulse and pulse plasma treatment technologies are relatively immature, the above cost estimates are clearly very approximate.

Size, Cost, and Complexity

An electric pulse treatment system that meets System A requirements would be approximately 2.5 m wide, 1.5 m high, and 1.0 m deep, and weigh about 1.5 tons, mainly due to the transformers. Such a system would be designed for long lifetime (more than 10^5 hours), and no maintenance would be required over this period. Since the system would be a push-button device, no training in its use would be needed.

The gross volume of a pulse plasma treatment unit for System A would be between 4 and 6 m^3, with a weight of about 4,500 kg, including safety screening and controls. Such a system would be self-monitoring with automated shutdown and out-of-service alarms, and would not require attended operation. Maintenance could be scheduled while a vessel was in port, but no information is available on the mean time between failures. One or 2 days of training would be needed to acquaint engine room personnel with the device and its safety provisions.

Monitoring

Both systems monitor energy flow, but additional tests (and equipment) would be needed to measure the mortality rates of specific organisms.

ACOUSTIC TECHNIQUES

Ultrasound in the appropriate frequency and power ranges destroys microorganisms in liquids by means of localized mechanical stresses resulting from cavitation. Ultrasonic treatment systems use transducers to generate alternating compressions and rarefactions in the liquid to be treated. The resulting cavitation is influenced by frequency, power density, time of exposure, and the physical and chemical properties of the liquid. Optimum frequencies for destroying microorganisms are reported to be in the lower range of ultrasonic frequencies, from 15 to 100 kHz. The application of ultrasound treatment to large volumes of liquid has given variable results. Treatment effectiveness decreases with increasing distance from the transducer as the energy density in the liquid decreases. The efficacy of ultrasonic treatment increases with exposure time and can also be influenced by resonance effects due to container geometry.

Safety

Any shipboard ultrasonic treatment system would be fully sound-insulated and shielded, even though the operating frequencies are not considered harmful.

Effectiveness

An appropriately designed ultrasonic system could totally destroy a broad spectrum of fungi, yeasts, and pathogenic bacteria. As regards higher organisms, pilot-scale ultrasonic treatment tests on zebra mussel veligers in water flowing at rates between 50 and 500 gpm gave variable results. The kill rate was small for short treatment times (less than 60 s), but increased to 100 percent with a treatment time of 12 min. It was concluded that such a system would not be practical for a power-plant intake application. It has been shown that high frequency sound (approximately 125 kHz) consistently elicits strong avoidance responses from certain fish (alewives [*Alosa pseudohargenus*] and juvenile American shad [*Alosa sapidissima*]), but the fish are not killed on entering an ensonified region.

The committee concluded that, despite encouraging results in killing microorganisms, the limited effectiveness of acoustic methods in destroying higher organisms renders this technique generally unsuitable for shipboard ballast water treatment.

Status of Technology

Ultrasound has been used to control micro-organisms in the food, dental hygiene, and water-treatment industries. A feasibility study was conducted in the mid 1970s using ultrasound for shipboard waste water treatment, but effective cavitation and resulting sterilization were not achieved for the volumes of water involved. Given the importance of the treatment chamber and geometry in determining treatment effectiveness, it is clear that a large-scale shipboard system would need to be carefully designed. The possibility of using ultrasound to destroy micro-organisms in shipboard fuel systems is currently under investigation. A prototype system capable of handling 3,000 gal/hr is under development. Current ultrasonic systems could not handle the anticipated ballast water flow rates of 2,000 to 20,000 m^3/h in a shipboard environment, and scale-up is likely to be problematic. Acoustic treatment—if deemed appropriate for specific applications—would be more readily implemented at a shore-based treatment facility with adequate tank storage. A closed-down oil refinery or tank farm might provide an appropriate configuration.

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APPENDIX G

Treatment Options Query

A ballast water treatment options query developed by the committee, which is provided below, was sent to suppliers and developers of candidate water treatment systems and to research organizations.

BALLAST WATER TREATMENT OPTIONS QUERY

System A: Flow rate of 2,000 cubic meters per hour, and tank volumes up to 25,000 cubic meters with residence times as short as 24 hours

System B: Flow rate of 20,000 cubic meters per hour, and tank volumes up to 25,000 cubic meters with residence times as short as 24 hours

For each of the two system flow rates described as System A and System B above, please complete the following query.

Technology Requirements and Capabilities

1. Treatment technology name and developer or vendor:
2. Typical application of technology (e.g., drinking water sterilization, etc.) OR is this technology at the experimental level:
3. Typical treatment endpoints or goals (e.g., 95 percent to 99.9 percent removal or sterilization, species-specific biocide, etc.):
4. Typical equipment requirements (configuration requirements such as in the tank or engine room):
5. Space Requirements (length, width, and height in either feet or meters would suffice):

6. Costs—capital, operation and maintenance, unit treatment costs:
7. System operation, maintenance, and reliability:
8. Training/Manning:
9. Monitoring capabilities (monitoring capabilities built into the system, or requires additional equipment):
10. Residuals formed during the use of the technology (chemicals or gases remaining after the process):
11. Retrofit capabilities (requires dry-docking a vessel, or can be retrofitted while afloat):
12. Safety concerns (human health threat or danger in application of this technology?):
13. Similar installations (any examples of where the equipment has been used or tested successfully):
14. Special permit requirements:

Application Considerations of Technologies

1. Effects of salinity levels of 0 to 30 parts per thousand or specific gravities of 1 to 1.025:
2. Effects of temperature (does temperature have any impact on the operation of the proposed equipment?):
3. Effects of sediment loads up to 10 percent (sediment load directly impacts the turbidity, and this may have a negative impact on some types of treatment such as infrared):
4. Effects of increases in treatment goals on how well the system performs:
5. Effects of ship motions:

RESPONSES

Completed responses were received from the following suppliers, developers, and research organizations:

Alten Water Treatment Corporation, Palo Alto, California: ozone treatment (P)[1]

Aquafine Corporation, Valencia, California: ultraviolet treatment

Center for Advanced Ship Repair and Maintenance (CASRM), Inc., Norfolk, Virginia: pulsed electric field treatment (P)

Defence Research Establishment Atlantic, Halifax, Nova Scotia, Canada: ultrasonic treatment

[1] (P) indicates that a representative from the named organization also gave a presentation to the committee at one of the technology workshops (see Appendix B).

Enviro-Plasma, Inc., Fairfax, Virginia: pulse plasma treatment

E.T. Ventures, Johns Island, South Carolina: modified bentonite clay for hydrocarbon remediation and water filtration applications (P)

Scienco Inc., St. Louis, Missouri: chlorination

ZMT Industries, Inc., Fort Wayne, Indiana: magnetic treatment (P)

The following organizations provided information on candidate treatment technologies but did not complete the query:

Center for Biological Macrofouling Research, University of Texas at Arlington, Arlington, Texas: oxygen deprivation

Culligan International Company, Northbrook, Illinois: filtration systems

Hayward Industries, Inc., Elizabeth, New Jersey: filtration systems

Sonalysts, Inc., Waterford, Connecticut: acoustic and ultrasonic systems (P)

T.P. Technology plc, High Wycombe, Buckinghamshire, United Kingdom: use of silver and copper ions as biocides (P)

APPENDIX H

Emerging Monitoring Technologies

ADENOSINE TRIPHOSPHATE ANALYSIS

Perhaps the most highly developed monitoring method for viable biological activity is the measurement of adenosine triphosphate (ATP). This analysis has been used by biologists for many years to determine the presence or absence of viable activity. The biochemical energy system, ATP, is only present when biological activity is occurring; ATP is absent from inactive biological material. Analysis for ATP is well defined and is performed with common laboratory equipment. There has been little change in ATP methods over the past five years. ATP must be extracted from cells to be stabilized before analysis. This procedure has been slightly simplified with the use of nitric acid as an extractant and new photometers have been developed for field use. These handheld photometers are relatively inexpensive ($400) and allow the presence of ATP to be determined after extraction.

ATP levels decrease over a period of minutes or hours after cell death. Therefore, the technique is awkward to use for disinfection processes, as some ATP remains for a variable period of time after treatment. However, the technique can be calibrated for a given disinfection process to account for the time variability of measurements. The ATP content of cells varies widely with cell size; therefore, ratios of nucleic acids or protein to cell size are perhaps most representative of population viability. Such ratios would need to be generated through research efforts for standardized monitoring of ballast water microbial populations. Despite the aforementioned limitations, the ATP analysis technique does have universal application and has been shown to be effective for planktonic and benthic organisms, including both heterotrophic and autotrophic procaryotes and eucaryotes (Herbert, 1990).

RNA/DNA ANALYSES

A second group of promising monitoring techniques includes the determination of RNA/DNA ratios, enzyme analyses, and measurements of lipid content. These analyses of eucaryotic or procaryotic populations can be streamlined, but all currently require extractions. The analyses for each of the biological materials discussed above are simple to quantify and could be adapted for use on board ship. As with ATP monitoring, the analyses would need to be correlated with actual ballast water populations for predictive purposes. These analyses would probably require some preparation on the part of crew members, but the extractions and chemical additions could be simplified to be analogous to swimming pool analyses. Specifically, safe, premeasured portions of chemical additives and small amounts of glassware could be supplied to generate a visible residual. The residue could then be readily analyzed colorimetrically on board ship.

Surrogate methods of analysis, such as ATP analysis and determination of RNA/DNA ratios, may be particularly useful if on board treatment procedures such as filtration or disinfection are used. In these cases, it would only be necessary to determine the absence or presence of biological materials such as ATP or DNA to indicate a high degree of treatment effectiveness. Such monitoring processes will probably be the least expensive to implement on board ship but will require some training to facilitate the analysis by crew members.

FLOW CYTOMETRIC TECHNIQUES

A promising technique that could eventually be applied to monitoring ballast water for unwanted biological organisms is flow cytometry. This technique uses a modification of a typical Coulter counter system and can be operated in a flow-through mode. The equipment allows for a small passage of water through an aperture of preset size (usually 2 to 20 μm). Organisms that pass through this aperture can be measured by the cytometer. The system not only quantifies the size and volume of organisms passing through the orifice, but can also detect the natural fluorescence associated with the presence of chlorophyll. Therefore, flow cytometry can be used to quantify all microorganisms without an outside excitation. This equipment is currently available commercially and has been installed and operated on research vessels where its portability, while requiring some improvement, has been proven.

A flow cytometer could also be used to identify the presence of specific organisms if either dyes or DNA/RNA probes were added to the water prior to measurement. For instance, dyes added to a sample of water before passage through the flow cytometer affect the membrane potential of the cells. This potential can be detected by the flow cytometer, and it will be different depending on whether a cell is active or inactive. Because inactive cells have no induced membrane potential, the viability of organisms passing through the cytometer can be determined.

A sample of ballast water incubated with specific DNA probes will hybridize with known sections of a genome of specific target organisms, such as unwanted dinoflagellates. These organisms can be detected by the cytometer. Therefore, specific taxonomic groups can be identified automatically using a flow cytometer with the addition of RNA or DNA probes. A great amount of research work is currently going on in the United States to develop specific DNA probes as a tool for ecological application (see, for example, Fell et al., 1992).

Because of its specialized nature, the main drawback to the use of flow cytometry is expense, and unless a simplified version becomes available it is not clear that ships would voluntarily use such equipment on board.

OTHER AUTOMATED TECHNIQUES

Other possible procedures that may be adapted for automated shipboard use to determine the quality of ships ballast water are immunofluorescence, specific DNA probes, and extractable lipid phosphate analyses. These techniques are of interest because they allow identification of specific taxonomic groups and ships could determine if they had a specific organism within their ballast water that would not be accepted in a port of call. An analytical procedure with this capability would obviate the need for extensive research efforts to correlate surrogate analyses to the presence of specific unwanted species. Development of automated forms of these analyses would permit a specific identification that could be rapidly implemented to assist in controlling introductions of selected species.

Using specific DNA probes in flow cytometry was discussed above. Research on lipid phosphates has not received much recent attention, but information is available from previous research. Lipids serve as a major form of energy storage in plant and animal tissues. They are the principal components of membranes and maintain the structural integrity of cells. Therefore, monitoring the presence or absence of lipids indicates the overall biological activity of a water sample. Lipids are routinely separated and analyzed using high-pressure liquid chromatography (Christie, 1987). Both DNA probes and lipid phosphate techniques would require more development before they could be used as a routine tool for monitoring ballast water.

Perhaps the most promising of the group, however, is the immunofluorescence technique that uses antigen-antibody reactions to implant fluorescent molecules on viable biological material. This procedure is currently the subject of a substantial research effort by the U.S. Food and Drug Administration to identify unwanted toxic marine phytoplankton. Efforts are under way to identify antibody/antigen reactions specific to toxic phytoplankton such that fluorescent compounds can be selectively attached to these organisms. Once toxic phytoplankton have been "tagged" in this way, they are easily identified using either flow cytometry or simpler photometry. If refined, this technique would provide a method to identify selected members of the biota within ballast water samples. However, the high level of specificity is accompanied by high equipment cost.

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Glossary and Conversions

CONVERSIONS

There is no international standard on the unit of measurement for ballast. In this report ballast capacities are given in cubic meters. Appropriate conversion factors are listed below. These assume a freshwater specific gravity of 1.000 and a salt water specific gravity of 1.025. "Gallons" denote U.S. gallons.

1.0 cubic meter	= 1,000 liters (264.17 gallons)
1.0 cubic meter	= 8.386 barrels
1.0 cubic foot	= 0.028 cubic meters
1 barrel	= 31.5 gallons
1 barrel	= 0.119 cubic meters
1 barrel (crude oil)	= 42.0 gallons (no specific gravity given)
1.0 cubic foot (fresh water)	= 28.32 kilograms (62.5 pounds)
1.0 cubic foot (sea water)	= 29.0 kilograms (63.9 pounds)
1.0 long ton (= U.K. ton)	= 1.0160 metric tons (tonnes)
1.0 long ton (fresh water)	= 1.016 cubic meters
1.0 long ton (sea water)	= 0.99 cubic meters
1.0 gallons/minute (gpm)	= 8.02 cubic feet/hour
1,000 metric tons/hour (fresh water)	= 264,170 gallons/hour
1,000 metric tons/hour (fresh water)	= 8,386 barrels/hour
1,000 metric tons/hour (sea water)	= 257,727 gallons/hour
1,000 metric tons/hour (sea water)	= 8,172 barrels/hour

GLOSSARY[1]

Adenosine triphosphate. The energy storage molecule of most living systems.

Aerobic. The condition in which oxygen is present.

Aft, after. Toward, at, or near the stern.

Alien. A species that is not native to an area (see nonindigenous).

Anaerobic. Living in the absence of free oxygen.

Anoxic. Without oxygen.

Aquaculture. The culture of aquatic organisms.

Arrow worm. A planktonic carnivorous marine invertebrate of the phylum Chaetognatha.

Astern. Behind or from behind the vessel.

ATP. See adenosine triphosphate.

Ballast. Any solid or liquid weight placed in a ship to increase the draft, to change the trim, or to regulate the stability. For the purposes of this study the term ballast includes sediment, which is the debris that comes out of suspension in ballast water and accumulates on horizontal surfaces in ballast tanks.

Ballast tank. A watertight enclosure that may be used to carry liquid ballast.

Bending moment. The product of a force acting at a distance from a support or reference point. The vertical bending moment tends to bend the hull in the vertical plane.

Benthic (benthos). Living on or in the bottom of the ocean.

Bilge. Intersection of the bottom and the side; may be rounded or angular as in a chine-form hull. The lower parts of holds, tanks, or machinery spaces where bilge water may accumulate.

Bilge and ballast system. A system of pumps and piping generally located in the holds or lower compartments of the ship. This system is used for pumping overboard accumulations of water in holds and compartments and for filling, emptying, and redistributing water ballast.

Bilge water. Stagnant water collected in the lower parts of vessels.

Biodiversity. The variety of different types of organisms living in a given area.

Biota. The living organisms of a region.

Boreal. Of, relating to, or located at high latitudes.

Borer. An organism that damages the structural integrity of wood or other materials by boring holes into it.

Bow. The forward end of a vessel.

Brake horse power (Bhp). The power produced by the prime mover before entering any reduction gear, if installed.

[1] The definitions of shipping terms draw extensively on H. Benford. 1991. Naval Architecture for Non-Naval Architects. Jersey City, New Jersey: The Society of Naval Architects and Marine Engineers.

Bulk carrier. A vessel designed to carry dry-bulk cargoes, such as ore, coal or grain.

Bulkhead. A term applied to the vertical partition surfaces that divide the inside of a vessel into compartments, rooms, and tanks. The various types of bulkheads are distinguished by their location, use, tightness orientation, etc. (e.g., forepeak, transverse, longitudinal, or watertight).

Cell guides. Vertical tracks within the cargo hold of a freight (container) vessel designed to assist loading, unloading, and stacking of containers.

Centerline. The middle line of the ship. extending from stem to stern. The centerline plane is the reference for transverse measurements.

Chaetognaths. A phylum of small carnivorous planktonic organisms.

Classification society. A private, quasi- governmental organization that formulates rules for the construction of ships, monitors their construction, and carries out periodic inspections on ships in service to assure their continued seaworthiness (e.g., American Bureau of Shipping, Lloyd's Register of Shipping, etc.).

Clean ballast. Ballast carried in cargo tanks after a crude oil wash, as contrasted to segregated ballast, which is carried in dedicated tanks.

Clingage. Residue on internal cargo tank structural members after cargo has been discharged.

Container ship. A vessel designed to carry cargo that is prepacked in large trailer boxes to expedite loading and unloading. The containers typically move to and from the shore terminals on wheeled chassis/straddle carriers.

Copepod. Small crustacean of the order Copepoda; the dominant planktonic herbivore.

Deadweight. The carrying capacity of a ship at any draft and water density. Includes the weight of cargo, lubricating oil, fuel, fresh water in tanks, stores, passengers and baggage, crew and their effects, and temporary ballast.

Deballasting. To release ballast from a vessel by gravity or pumping.

Deck. A horizontal surface in a ship corresponding to a floor in a building.

Deep tank. A tank extending from the bottom or innerbottom up to or higher than the lowest deck. They are often fitted with hatches so that they may carry cargo as well as fuel oil, ballast water, or liquid cargo.

Demersal. Living close to the bottom of the sea.

Diatom. Microscopic autotrophic organism of the algae class Bacillariophyceae characterized by being enclosed in a two-valve siliceous capsule.

Dinoflagellate. Microscopic organism of the order Dinoflagellata possessing two locomotory flagellae.

Dispersal vector. Mechanism that transports organisms from one region to another.

Displacement, light. The weight of the ship complete including hull, machinery, outfit, equipment, and liquids in machinery, but no deadweight items.

Displacement, loaded. The weight of the ship when floating at its greatest allowable draft, the sum of the light ship displacement and the deadweight.

Displacement, molded. The weight of water displaced by the volume of the ship below the waterline measured to the inner surface of the shell plating, without appendages.

Displacement, total. The weight of water displaced by the volume of the ship below the waterline measured to the outer surface of the shell plating and including all appendages.

Diurnal. Daily, or every 24 hours.

DNA. Deoxyribonucleic acid: the genetic material in (almost) all organisms.

Double hull. A structural arrangement featuring both inner sides and inner bottom.

Draft. The distance the ship extends below the waterline measured vertically to the lowest point of the hull, propellers, or other point. When measured to the lowest point, it is the extreme draft; when measured at the bow, it is the forward draft; when measured at the stern, it is the after draft. The average of the forward and after drafts is the mean draft; the mean draft in the full load or ballast condition is the load or ballast draft.

Dry-bulk cargo. Commodities, other than in liquid form, that are carried aboard a ship without benefit of packaging. Coal, grain, and various ores are examples.

Dynamic stability. The ability of a body to remain upright when subjected to various external disturbing influences, such as wind and waves.

Estuary. A partially enclosed coastal embayment where fresh water and sea water meet and mix.

Euryhaline. An organism able to live in an environment of widely varying salinity.

Exotic. See nonindigenous.

Flag state. A nation where ships can be registered (see port state).

Flow cytometry. Technique to quantify the size and volume of organisms and detect natural fluorescence associated with the presence of chlorophyll.

Fore. A term indicating location or that portion at or near the bow. Also that part lying between amidships and the bow.

Fore-and-aft. Aligned with the length of the ship; longitudinal.

Forefoot. The lower end of the ship's stem where it curves to meet the keel.

Forepeak. The watertight compartment at the extreme forward end. The forward ballast or trimming tank.

Forward. In the direction of the sterm or bow.

Fouling organism. An organism that attaches to hard surfaces such as boat bottoms.

Founder. To sink and go to the bottom.

Freeboard. The distance from the waterline to the upper surface of the freeboard deck at the side.

Free surface. The condition of liquid without any constraints on its upper surface, which allows the liquid surface to incline as the ship lists or rolls, making the ship less stable.

Gallons per minute (GPM). A common measure of volume flow rate in fluid handling systems.

General cargo. Goods to be transported in a mixture of forms, but usually packaged in some way other than container boxes.

Grible. Isopod (crustacean) that eats wood and can destroy wooden structures underwater.

Hatch, hatchway. An opening in a deck through which cargo and stores are loaded and unloaded.

Heave. A vertical translation motion of a vessel.

Heel. The inclination of a ship to one side; also list.

Heeling tanks. A pair of tanks, port and starboard, used to control the heel of a vessel, particularly to keep the container guides vertical during the loading and unloading of container vessels.

Holds. Space below deck for the stowage of cargo; the lowermost cargo compartments.

Hull. The structural body of a ship, including shell plating, framing, decks, bulkheads, etc.

In ballast. The condition in which the vessel is operating with ballast and no cargo.

Inboard. Inside the ship; toward the centerline.

Inoculation. Release of an organism in a new environment.

Introduction. Establishment of a reproducing population of an organism in a new region.

Invertebrate. An animal without a backbone (vertebral column).

Keel. The principal fore and aft component of the strip's framing, located on the centerline of the bottom and connected to the stern and stem frames.

Knot. A unit of speed, equaling 1 nautical mile (1,852 m or 6,076.1 ft) per hour; one minute of latitude at the equator.

Lee. The side away from the wind.

Lightering. The transfer of loads to smaller vessels that can enter shallow ports.

Liquefied gas carrier. A vessel designed to carry gas that has been liquefied by being compressed or cooled. Liquefied natural gas carriers or liquefied petroleum gas carriers are examples.

List. The inclination of a ship to one side; also heel.

Loading computer. An onboard computer that calculates the drafts, trim, and bending moment on the hull for any condition of loading cargo, stores, and ballast.

Loading head. The terminus of the pipe or cargo manifold on a vessel to which a hose assembly is connected to the shoreside facility for loading and discharge of cargo.

Loading manual. A shipboard document that defines acceptable ways of loading cargo, stores, and ballast considering drafts, trim, and bending moment.

Loadline. The deepest draft to which a vessel is allowed to load.

Longitudinal stability. The branch of stability having to do with the tendency of a vessel to trim.

Meroplankton. Planktonic organisms that spend only part of their life cycles in the plankton.

Metacenter, transverse. The intersection of a vertical line through the center of buoyancy (center of underwater volume) of a heeled vessel with the centerline of the vessel.

Metacentric height, transverse. The distance from the center of gravity of the vessel to its transverse metacenter (GM_t). If this distance is positive at zero heel the vessel is initially stable.

Neritic. Living in inshore or coastal waters, as opposed to the open ocean.

Nonindigenous. Not native to an area.

OBO. Abbreviation for a vessel designed to move flexibly between the carriage of oil, bulk cargoes, and ore.

Oligohaline. Waters with a salinity of 0.5 to 5.0 parts per thousand.

Panamax. The largest size vessel of a particular type that can transit the Panama Canal.

Pelagic. Living in the water column (contrasted with benthic).

Phytoplankton. Planktonic plants.

Period of roll, rolling period. The time it takes a vessel to make a complete roll, that is, from port to starboard and back to port again.

Pitch. A fore and aft vertical plane rotation motion of a vessel about a transverse axis.

Plankton. Those organisms free-floating or drifting in water whose movements are determined primarily by water motion.

Plankton net. Fine mesh conical nets dragged in the water to collect plankton.

Plasma arc. The plasma is a mass of extremely hot ionized gas formed by passing argon, or some other suitable gas, through a constricted electric arc.

Polychaete worms. Common marine segmented worms that comprise a large proportion of benthic communities on soft bottoms.

Port. Referring to the left side of the vessel looking forward.

Port state. A nation in whose port a vessel enters, as contrasted to a flag state, which is the nation in which the vessel is registered. The port state has the right under international law to enforce a convention (such as MARPOL) to which it adheres on any ship entering its ports and to initiate proceedings in the event of a violation.

Potable. Fit for drinking.

Propeller. Revolving screw-like device used for propelling ships through water or aircraft through air.

Protists. Eukaryotic organisms comprised of a single cell.

Range of stability. The angle of static heel a vessel may undergo without capsizing.

Reballast. To load water ballast back on a vessel after deballasting.

Red tide. The name given to massive blooms of dinoflagellates in which the concentration of the organisms is such that the water becomes discolored and toxins are often released in sufficient quantities to affect other marine organisms.

Registered tonnage. Legally prescribed measure of a vessel's internal volume; originally in units of 100 ft^3 (see tonnage, gross and tonnage, net).

RNA. Ribonucleic acid, an essential component of genetic function in all organisms.

Roll. A transverse vertical plane rotation motion of a vessel about a fore and aft axis.

RO-RO (foll on, roll off). Abbreviation for a vessel designed to carry vehicles, so arranged that the vehicles can be loaded and unloaded by being driven or rolled on and off on their own or auxiliary wheels, via ramps.

Rotifers. Small planktonic or benthic organisms with anterior cilia on a disk.

Salinity. The amount of dissolved salts in seawater.

Sea chest. An enclosure, attached to the inside of the shell plating and open to the sea, providing the connection of a piping system to overboard.

Seaworthy. A legal term implying that a vessel is capable of safe passage at sea.

Segregated ballast. Ballast tanks that are used exclusively for carriage of ballast; a vessel designed to carry ballast in segregated tanks.

Shear. Parallel forces acting in opposite directions. Also the vertical plane curve of a deck.

Slamming. Heavy impact resulting from a vessel's bottom near the bow making sudden contact with the sea surface after having risen above the surface due to relative motion. Similar action can occur due to the rapid immersion of the bow on vessels with large flare.

Stable, stability. The condition in which a body will move back to a condition of equilibrium when given a small initial movement away from this condition.

Starboard. Referring to the right side of the vessel looking forward.

Static stability. The tendency for a body to remain upright when floating in calm water with no external disturbances.

Stem. The bow frame forming the forward most part of the ship.

Stern. The after end of the ship.

Storm ballast tank. A compartment, usually a cargo hold, used only occasionally when a vessel needs to achieve a deep ballast condition for safety in heavy weather.

Strain. Deformation resulting from stress on a body.

Stress. Force per unit section area producing deformation in a body.

Stripping. the operation of removing the final portion from a tank not removed by the primary discharge system.

Symbiont. An organism living in symbiosis.

Synanthropic. Associated with humans.

Tanker. A cargo vessel designed to carry liquid cargo in bulk.

TEU. Twenty-foot equivalent unit, used to describe the standard unit of containerization.

Ton. A unit of weight; a long (gross) ton equals 2,240 lbs; a short (net) ton equals 2,000 lbs; a metric ton (or tonne) equals 2,204.6 lbs.

Tonnage, gross. An approximate measure of a vessel's total volume. A function of the hull volume; originally in units of 100 ft^3.

Tonnage, net. An approximate measure of a vessel's money-earning volume. The gross tonnage with the deduction of the machinery spaces and certain other volumes. Originally in units of 100ft^3.

Tonne. A metric unit of weight equal to 1,000 kgs force or 2,204.6 lbs.

TPH. Tonnes per hour.

Transverse stability. The branch of stability having to do with the tendency of a vessel to resist heeling and capsizing.

Trim. The difference between the drafts; the after draft minus the forward draft. Trim by the stern is positive; trim by the head or the bow is negative.

Trimming tank. A tank near the end of the ship carrying fuel or water and used to control the trim of the vessel.

Turbidity. Amount of light-reflecting material in suspension in water.

Turn of the bilge. A rolled plate section that transitions the flat bottom of a ship to the side. Usually a quadrant of a circle that forms the outer boundaries of the double bottom tank.

ULCC. An ultra-large crude oil carrier; over about 300,000 DWT (deadweight tonnes).

Unstable, instability. The condition in which a body will move further away from a condition of equilibrium when given a small initial movement away from this condition.

Vertical migration. Diurnal vertical movement of pelagic organisms in the water column toward the surface at night and down to greater depth during the day.

VLCC. A very large crude oil carrier of between about 150,000 and 300,000 DWT (deadweight tonnes).

Waterline. A horizontal line on the vessel's side when afloat. Any intersection of a horizontal plane and the molded form of the hull.

With ballast. The condition in which the vessel is operating with cargo and some ballast.

Zooplankton. Planktonic animals.

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