Engineering Controls for Ballast Water Discharge: Developing Research Needs

Report of a workshop
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Preface

A group of environmental engineers, environmental scientists and water resources engineers, all experienced in water supply and treatment, met in a workshop in Seattle, WA with a similar group of engineers and scientists experienced with marine systems and ballast water discharge research. The objective of the meeting was to discuss ballast water (BW) problems, concentrating on the engineering options for control of discharges and seeking the fresh perspective that experts in the relatively established field of water supply could bring to the emerging, difficult problems associated with ballast water discharge. The specific objective was to develop research needs to address these problems. The workshop was held over three days in April, 2003.

The first day involved presentations about ballast water problems and the constraints on the control options. Marine biologists, microbiologists, environmental engineers and marine engineers presented their views. Current and proposed regulations for the US and the International Maritime Organization were discussed, and research on discharge controls was described by researchers and by scientists involved in administering research programs. A ship was visited to better understand the physical constraints for installation of on-board treatment devices and to hear about ballast water management from the viewpoint of the ship's personnel.

The second day of the workshop was divided roughly into three segments. In the morning we reviewed the previous day's presentations, asking questions and discussing thoughts about the problem. Subsequently the participants assembled into breakout groups charged with discussing the problem from three points of view to develop research needs addressing: 1) possible criteria and end points for treatment or discharge of ballast water to the environment and associated monitoring needs, 2) technological approaches for BW control in the near term and over longer times as new vessels come into service, and 3) opportunities for systems approaches to analyze costs, benefits and risks and for using other aids in decision making at all stages of establishing regulations and implementing BW control. The groups reported their main findings, followed by substantive discussion. On the final morning, each participant was asked to select a specific issue of concern and possible role for research in addressing it. These were also discussed by the group.

The following report is based on the deliberations of the group. However, it does not follow the organization of the workshop deliberations. Rather, a synoptic view of ballast water problems, management and discharge control options is presented, followed by three sections addressing our views of research on (1) systems research opportunities to aid decision making, to refine estimates of risks, costs and benefits associated with discharge and control options, and to identify and evaluate the wide range of management options, (2) the near term problems in meeting current or expected regulations and constrained by the structures of existing vessels, and (3) the longer term problem where stricter regulations are envisioned and where new vessel design, new treatment technology, and new management systems are possible.

Since the workshop significant developments have taken place with publication in the US of proposed rules for mandatory ballast water management practices and of the intent to establish a ballast water discharge standard. In addition, the International Maritime Organization (IMO) has adopted a convention for control and management of ballast water. These developments are noted in the report, and to some extent, their implications on research needs are discussed.

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Executive Summary

Ballast water (BW) has been identified for nearly 20 years as a major vector for introduction of invasive aquatic organisms. The costs and ecological damage associated with some past introductions have been very large, and there is much evidence that invasive species continue to be introduced, perhaps at an increasing rate.

Control of ballast discharges is passing from a stage of voluntary measures and voluntary reporting by ships in US waters to mandatory ballast water management practices under United States Coast Guard (USCG) regulations. There is a timeline for implementing a ballast water performance standard under the International Maritime Organization (IMO) convention for ballast water management. Until that time, which ranges from 2009 for some new vessels to 2016 for some existing vessels, BWE is an accepted management practice.

Available technology for BW discharge control is not at a stage where it can be applied reliably. The most common current practice is empty-refill or flow-through ballast water exchange (BWE). Continued research is needed to better assess biological effectiveness, to establish hydraulic exchange performance of tanks, and to develop protocols for certifying operational practices for tanks on vessels. Use of biocides to kill organisms in ballast tank sediments and on surfaces also merits study as one approach to improve the biological effectiveness of BWE.

Treatment technologies for existing vessels also are in need of additional research. Treatment approaches for inactivation of organisms include biocides, ultraviolet radiation and heat applied to BW during ballasting or deballasting, or in-tank during voyage. Progress in developing on-board technologies for physical removal of organisms has been slow because of the severe physical constraints in installing equipment on existing vessels and treating high flow rates of BW (ranging from 300 to 3000 m^3/hr).

Development of all technologies has been slowed because of lack of facilities and funds for research and because of slow progress on finding suitable test organisms or surrogates for treatment efficacy. Indeed, there is no consensus on whether treatment should address pathogenic bacteria or should focus on potential invasive species. Little research has been done on possible environmental impacts of treated BW discharge.

Options for incorporating effective BW management in new vessel designs and/or new port facilities seem very attractive, but they are not well developed. Requirements for multiple ballasting operations for some vessels and some ports may mean that more than one BW discharge control option needs to be available to ships. It is important that requirements for existing vessels in the near term do not preclude better options for the long term.

Fundamental and developmental research on BW discharge control is needed, in some cases urgently. The problem is international in scope, and efforts in the US should be coordinated with research in other countries. In many aspects, BW discharge control research can be pursued by investigator-initiated projects, funded through a competitive, peer-reviewed process, such as that used by the National Science Foundation. Other aspects of BW discharge control development would benefit from a research agenda, developed by all stakeholders, including researchers, and from specific projects, described by requests for proposals (RFPs) with competitive, peer-reviewed selection of research contractors.

A larger group of researchers, knowledgeable about BW problems and involved in BWDC research, is needed.

The Problem Synopsis

A good portion of the workshop was devoted to presentations about the ballast water and aquatic nuisance species (ANS), to the current status of regulations and research, and to the options for engineering controls. This section is intended to present an overview of the problem of ballast water discharge and the options for control. In subsequent sections the engineering control options are developed in more detail, along with research approaches that were discussed and recommended by the workshop participants.

The economic impacts of invasive species are immense in the US, and a significant fraction of the invasions can likely be attributed to marine transportation, especially to ballast water discharges.

Ballast water discharge is also an international problem. ANS identified with ballast discharges have been identified in most maritime nations; the IMO has adopted (February, 2004) an international convention that would regulate marine shipping to control ballast water and introduction of ANS.

Ballast water discharges are associated with ecological disruption of aquatic communities in and near ports, with economic impacts of invasive species, and with transport of human pathogens, notably including toxic strains of *Vibrio cholerae.*

Ballast tanks may receive a very wide variety of planktonic organisms from the marine, estuarine or fresh water locale where ballast is taken on. The organisms have complex life cycles and interactions with each other. While many taxa tend to die away during transport, some maintain stable populations and some may increase. Ballast tanks may sustain populations of some marine organisms as biofilms, in sediments and as planktonic forms.

Without removal or inactivation, organisms are discharged when the vessel deballasts. The factors that may lead to a successful invasion by a nonindigenous species (NIS) are very poorly understood, so there is little ability to predict the probability of a species becoming established and even less ability to predict the ecological disruption and economic damage that may result. Thus, it has often been assumed that introducing any and all non-native species represents an unacceptable risk.

The problem has been addressed in the US through legislation mandating regulation and control of ballast water. Regulations include implementing best management practices, record keeping of ballast water handling and voluntary implementation of empty-refill or flow-through ballast water exchange (BWE). Compliance with voluntary reporting and BWE apparently has been low. The US Coast Guard now proposes mandatory ballast water management programs, usually involving BWE. The US regulations must be consistent with the IMO convention adopted February 2004, which allows BWE exchange as a primary method until 2009 with phasing out in favor of a performance standard between 2014 and 2016. The performance standard requires <10 viable organisms per cubic meter of minimum dimension >50 µm, <10 viable organisms per milliliter size between 10 and 50 µm, and specific standards for toxicogenic *Vibrio cholerae* and indicator bacteria. Several states have established their own requirements for reporting, for BWE or other control measures.

Future requirements may take several approaches, including mandatory management practices, record keeping and reporting by all vessels. BW management practices would include offshore BWE, retention of BW with no discharge, use of an alternative treatment method, or discharge to a reception facility. Treatment of BW during uptake or discharge, or while on board, has also

been proposed with a variety of physical and chemical processes and devices. Of the alternatives, BWE is judged the practice most likely to be used in the near term.

BWE can be conducted as empty/refill exchange or as flow-through exchange. When low salinity BW is exchanged with open ocean water, BWE is likely to be reasonably effective in reducing risk of invasions for many species. However, BWE is not completely effective in removing planktonic organisms and is not very effective in controlling organisms that reach sediments or attach to surfaces in the tanks. Tanks also have complex shapes, baffling and varying inlet and outlet designs. It may not be possible to remove all water during emptying. Flow-through exchange is often specified to last for three hydraulic residence times, which would achieve 95% replacement of the BW if the tank was completely mixed. Because of the complex geometry, exchange effectiveness is not predictable, but needs to be measured. Density differences between BW and ocean water can affect BWE effectiveness.

Many on-board treatment systems are being developed. Among the promising approaches are treatments with biocide addition, ultraviolet radiation or heat to inactivate BW organisms. Physical separation devices have shown promise when used to remove BW organisms when discharging BW (or when taking on BW). However at this point, it can be argued that no method has been proven practical and effective for installation on existing vessels. In fact, criteria for effectiveness are not widely agreed on, nor are measures of environmental impact.

The Role for Research

The development of drinking water treatment technology, a model for problem-oriented research that many workshop participants shared, may be useful when approaching the issues associated with ballast water discharge. Water treatment research, extending over nearly 100 years, has focused on the common objectives of the drinking water industry, protecting public health, reliably meeting consumer demand, producing water that is clear, without objectionable taste, color or odor, and at a cost easily borne by consumers. Research has been strongly oriented to the objectives and constraints of the industry. It has ranged from knowledge-driven studies to understand scientific fundamentals to issue-oriented work responding to newly recognized contaminants to support the regulatory needs of the US Environmental Protection Agency (EPA). Individual scientists and engineers have been recruited to address the problems and have developed skills in aspects of chemical, physical, biological and engineering sciences, often working in multidisciplinary teams, identifying themselves as environmental engineers or scientists.

Research has been supported by federal agencies, in the past the US Public Health Service and now primarily EPA. The National Science Foundation has had a major role in supporting knowledge-driven research, and in recent years an industry organization, the American Water Works Association Research Foundation (AWWARF), has developed an important role in defining key research problems and funding work to address them. Research has been carried out at government labs, by private and public drinking water suppliers, by consulting engineering firms and, especially, at universities. In recent years the research infrastructure has responded repeatedly and rapidly as new water quality issues emerged, ranging from emerging pathogens, such as *Cryptosporidium* and *Giardia* and *E. coli* O157:H7, to disinfection byproducts, arsenic, perchlorate and corrosion of copper and lead. Drinking water has been a central focus for the discipline of environmental engineering because of continuing support for research and continuing demand for skilled environmental engineers and applied scientists.

The problem of invasive species and public health threats from ballast water discharges is important and difficult. It merits a research effort tailored to the issues. Some of the most important issues are associated with the control options, which fall close to the problems addressed by water quality engineers, water resources engineers and environmental scientists, and we see many similarities with the role of research in addressing drinking water and water supply issues.

The path forward for BW control can be seen, but not clearly. The economic and environmental costs of failure to control BW discharges are highly uncertain, but undoubtedly very high. The costs of control are also high. Control methods in the near term will increase operating costs for vessels, place new duties on ships' crews, and require investment in control technologies. In the longer term, new requirements for vessel design seem likely, either to facilitate installation of on-board treatment or to allow transfer of BW to shore-based facilities. There may also be good options for eliminating the discharge of BW in ports. Regulations adopted in the near future will illuminate part of the path, but may constrain options for the longer term. Efficacy and environmental impacts of control methods are not well understood; both fundamental and applied research is needed. Control approaches in the longer term would seem to depend on better understanding of the very complex system of global marine shipping, the opportunities for new vessel design and the performance requirements for control that may range from the 95% removal goal of BWE to complete removal or inactivation of all organisms in BW.

The research effort to-date on ballast water discharge control is not sufficient. In the US, funding has not been stable. Research programs have not been developed that are comprehensive or that have a clear view, seeking an optimal long-term solution. The near-term approach has been cluttered by vendor-driven offerings of devices and chemicals of unproven efficacy and of agency-driven desires to certify these technologies for rapid adoption. The workshop discussions were largely devoted to trying to clarify the issues that the research community needs to address.

Many of the research issues can and should be investigated at the bench-scale first, to provide a proof of concept and characterization of the problems and solutions. Bench-scale studies allow researchers to cost-effectively study the impact of selected control strategies and parameters of concern under controlled (ideal) conditions. Subsequent research should involve scale-up (non-ideality, real-world), from test-bed facilities to demonstration-scale (full-scale model) to full-scale implementation.

Two important qualifications on our report need to be stated. The first relates to the scope of the problem, and the second to our ability to address BW control.

First, BW discharge control is only part of a much larger picture of ANS. Other transmission mechanisms may be important in marine transportation, including organisms in sea chests, on hull and anchor chains, etc. And marine transportation is one of many ways that ANS can be transported to new locations where they may become established. These caveats notwithstanding, we believe control of BW discharge is significant, meriting the attention that it has received nationally and internationally, and requires a research program to find the best solutions.

Second, the workshop, intending to bring new perspectives to the problem, matched drinking water professionals with others already involved in BW management and control. The discussions were intense and productive, but it wasn't possible for the participants to assimilate the considerable information and research results that address BW issues. Thus some of our discussion and some of the issues raised reflect an incomplete understanding. However, we believe that our discussions provide a useful, valuable perspective on the near term control

approach, the opportunities for systems studies, and the path towards an optimal long term solution.

Systems Needs

At many junctures in the workshop, issues were raised where it seemed that better decision making methods might be useful, where a broader view of the problem would be productive, or where a multi-disciplinary view of a complex system seemed to be needed. In each of these areas, the tools that have been developed and applied by water resource systems engineers could be adapted and used. Tools from other systems engineers, working with large and complex systems in the military, aerospace, computer and information technology, should also be applied.

At the workshop the difficult discussions associated with the establishment of future US regulations and of finalizing the IMO convention were described. We learned of the biologists' and engineers' concerns about measuring and monitoring invasions, about the effectiveness of ballast water treatments, and compliance with standards. These problems, in particular, are at the intersection of biological, engineering and regulatory expertise; they are critical to effectively integrating BW treatment and regulations.

These concerns have not been solved easily. In each case, techniques for aiding decision-making by groups of experts could lead to consensus and establish acceptable procedures where there is broad agreement on the objectives. In some cases, development of decision support tools such as simulations and expert systems may be merited; in others, use of problem formulation and decision-making methodology is needed.

While the group felt strongly that control of ballast water discharges is very important, three aspects of the problem were identified for broad review. The costs and benefits of control and the risks of noncompliance must be assessed at regular and appropriate intervals. The review in 1996 by the National Research Council which underlies much of the subsequent effort is based on research that is a decade old.*

The problem of ballast water and invasive species is a far reaching and important issue and worthy of significant systems research, similar in purpose to the reviews of global atmospheric change, its impacts, and the policy options by Intergovernmental Panel on Climate Change. Such an effort should consider the US national and the international perspective on invasions, consider the range of vectors for ANS, but focus on the role of ballast water and its control. The scope of a review might include:

- the documented invasions, the associated damages, and the methods, cost and effectiveness of control efforts,
- the risks of ecological damage, economic impacts, or to the public health,
- the control strategies, their costs and likely effectiveness, including the costs of a fail-safe approach, addressing the consequences of invasions rather than of preventing them, and
- the future alternatives, not limited by proposed regulations and institutional constraints.

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* *Stemming the Tide: Controlling Introduction of Nonindigenous Species by Ships' Ballast Water,* Committee on Ships' Ballast Operations, National Research Council, 1996

The alternatives for BW discharge control also merit broad study. The efforts to remediate the current situation, with existing vessels, existing port facilities, and existing operational practices on vessels, must deal with difficult constraints. Without taking a broad, systematic review of the problem, ineffective and expensive solutions may be suggested. Currently, there are serious efforts to require implementation of on-board treatment systems that will be costly and may not, unfortunately, be effective. A systems approach may well be useful in better defining the objectives of management, identifying real as well as perceived constraints, identifying potential risks of alternatives, and selecting the best among solutions that are identified. The best solutions for the longer term—as vessel design can incorporate treatment and other control options, as on-shore treatment facilities can be built, as operational practices can be developed that utilize methods appropriate for particular vessels, shipping routes and ports, and as reporting, monitoring and enforcement become robust—may be very different from the best near-term approach. Defining this future merits multidisciplinary, systems-based study. The payoff in terms of better policies seems clear; the possible cost of decisions made now that rule out better options down the road is also clear.

The Near Term

Technologies and management practices will be strongly influenced by international conventions and national regulations. The outlines of acceptable practices and improved management can be seen, and there are knowledge gaps that need to be addressed to facilitate the development of effective control policies and to support the regulations that will be put forward. Currently, proposed USCG regulations and the IMO convention point towards BWE and use of biocides as likely practices with existing vessels for many years.

Ballast Water Exchange

BWE is a current management practice that is likely to continue for many years—under the IMO convention until 2009 as the primary method and phased out between 2014 and 2016 depending on vessel ballast capacity. While the method falls far short of complete removal or inactivation of organisms in BW, it can often provide substantial protection. A few studies have evaluated survival of organisms in BW or have measured changes in numbers due to BWE. Much more work remains to understand BWE effectiveness, to establish simple protocols for measuring and certifying effectiveness, and to find robust data acquisition systems that can be used to report verifiable BWE operations conducted at sea.

Effectiveness requires understanding the mixing behavior of ballast tanks during empty-refill or flow-through exchange. Assuming that a criterion such as 95% replacement of BW can be found, both approaches would seem to require certification of BWE methods for each BW tank on every vessel, based on measurements or on calculations. Pumping through three times the volume, as specified in the IMO convention, may not achieve 95% replacement of BW in many tanks. Dye testing methods and reactor mixing models can be readily adapted to use with BW tanks, and testing protocols can be formalized for measuring tanks on existing vessels. A wide variety of tanks should be tested. The 95% exchange criteria should be critically evaluated against data for tank performance, and exchange protocols should be certified. The behavior of sediment and organisms during BWE exchange also needs further study to better understand biological effectiveness of BWE. The research agenda for BWE is developmental, rather than fundamental; it is quite clear and it is urgently needed.

Biocides

Biocides also are likely to have a role in BW discharge control. Since BWE is less effective against aquatic organisms that can settle into sediment or attach themselves to surfaces in the

tanks, occasional in-tank use of biocides may be needed for vessels using BWE. Biocides also are likely to be an acceptable management practice, if they can be shown to be effective, economic and free from environmental damage. Biocides, however, are less effective in a particle-rich setting, so their use may be limited by BW quality. Most biocides will need to be added as BW is taken on and will need to persist for long enough to inactivate organisms entrained in BW and, if used to enhance BWE, to inactivate organisms in tank sediments and on surfaces. Though not effective in conjunction with BWE in killing organisms in tanks, treatment with biocides during discharge is also a likely BW control approach.

Research needs for in-tank biocides span a gamut:

- technology development for shipboard handling of chemicals,
- understanding the efficacy of agents against the wide range of potential nuisance species, particularly in a particle-rich environment,
- understanding the role of BW quality on efficacy,
- understanding the fate of the chemical agents, the production of byproducts, absence of residual toxicity and other environmental impacts of discharging treated BW, and
- understanding the effects of chemical agents on the ship environment (i.e. corrosion)

The latter aspect seems most critical for adoption of biocide treatment. Knowledge of environmental fate and effects for even the best understood disinfectants, such as chlorine, apparently is lacking for application to seawater and discharge to waters in ports.

Other technologies may also have a role for use with existing vessels, especially vessels with relatively small volumes and low flow rate of BW. The technologies need development, evaluation and certification for adoption and use. There is a specific need for a test-bed facility to allow testing at pilot and demonstration scale, as technologies reach that stage.

Research for Long-Term BW Control

The workshop did not develop or even outline an optimum solution for BW control. Further, near-term regulatory decisions may preclude some options for the future, and monitoring, reporting and enforcement procedures must be strong enough to assure compliance. There are, however, many possibilities for effective control, and a great deal needs to be learned to make good decisions about engineering controls to reduce the risk of aquatic nuisance species introductions from BW.

In the preceding section, the need to find the best approaches for managing BW discharge was described. There is much to be done to develop and critically evaluate the alternatives. The following section presents some of the issues associated with some of the alternatives.

New Vessel Design

New vessel design seems to be the best route to overcome the severe constraints imposed by the design of ballast handling systems on existing vessels. Naval architects and marine engineers will have central roles in evaluating vessel design needs, working with regulatory agencies, ship owners, systems analysts and treatment experts. Among the options that need evaluation are:

- new designs that minimize need to discharge BW in ports or coastal waters,
- taking BW from, or discharging BW to, a shore-based treatment facility,
- developing systems for chemical treatment of BW, including chemical storage (or generation), chemical feed and perhaps, mixing in BW tanks,
- better design for emptying tanks and for improved flow-through exchange
- provide space to accommodate treatment devices, and

- providing more than one option for BW handling, perhaps including discharge to on-shore facilities, BWE, and treatment in-tank or during ballasting or deballasting.

The development of new vessel options appears to be the most important, perhaps the most difficult challenge in BW control. The options are many, but also are constrained. They have the potential to achieve much better risk reduction, compared to the near-term options, and to do so with shipboard systems that are efficient, effective and flexible. Preferred options must be acceptable to regulators and to the marine transportation industry, implying that a high degree of risk reduction can be assured and that it can be done with acceptable costs and operational requirements. If options can be clearly developed, refined and evaluated in the time frame of IMO guidelines and US regulations, then the industry can embark on a path to eliminate BW as an ANS vector as new vessels come into service.

On-Board Treatment

Development of on-board treatment alternatives seems the most challenging of the long-term options. On-board treatment is included in prospective US regulations and in the IMO convention, as well as by states such as California and Washington, so the development of these alternatives is also urgent. The performance standard of the new IMO convention, adopted after our workshop, will help guide development. It requires removal of organisms >50 µm to a very low level, but is much less stringent for organisms between 10 and 50 µm. When fecal contamination is present, disinfection to reduce specific pathogen and indicator bacteria will be needed. The time-line for meeting the performance standard allows for a significant scientific and technical research program to overcome the expected challenges.

Metrics for Measuring Efficacy

In all systems, metrics for effectiveness are needed. Sometimes, ambient organisms can be used to demonstrate effectiveness, but in many cases surrogate (indicator) test organisms or surrogate parameters will be needed to evaluate process alternatives. We understand that progress has been made in this area, but engineering researchers will need very clear guidance on measuring treatment effectiveness. Inactivation technologies require metrics for several classes of organisms; separation technologies may use particle counts or surrogate particles to demonstrate efficacy.

The IMO performance standard, mandating <10 viable organisms per cubic meter of size >50 µm in minimum dimension and <10 viable organisms per milliliter between 10 and 50 µm, provides challenges in enumeration, size determination and determining viability. New "sensor technologies" or molecular methods may prove very useful for rapid detection of viable organisms and for detecting specific species or groups of organisms.

Inactivation technologies

Inactivation processes include addition of biocides (e.g. chlorine, ozone, iodine) or other chemical agents (e.g. for deoxygenation) as ballast is taken on or discharged, as well as use of physical agents, notably ultraviolet (UV) irradiation, in the same manner during ballasting or deballasting. For all biocide treatments discussed at the workshop, there seem to be many questions about the underlying chemical processes (e.g. active chemical disinfectant species during ozonation) with the range of ballast water quality (fresh, estuarine, marine, all with or without sediment) that can be encountered. There are unknowns about how biocides inactivate or kill organisms in seawater, about the role of water quality and the proper kinetic models for inactivation and dosage and contact time requirements, and—in particular—about the resistance of problematic organisms such as cyst-forming dinoflagellates.

In addition to questions regarding efficacy, there are large information gaps about environmental effects of the use of most biocides. There are environmental concerns about persistence of

biocides after discharge and about formation of byproducts from breakdown or from reactions of oxidizing agents. Disinfection research for drinking water, addressing a limited range of microorganisms and water quality, has been remarkably productive over the last 90 years, but with many twists and turns as concerns have arisen over disinfection byproducts, over resistant pathogenic protozoans, over growth of bacteria in water distribution systems and over corrosion. The problems with biocide use in ballast water are likely to be more similar than different, and a research effort seems needed, involving committed scientists and engineers working over many years.

Use of physical agents, such as UV radiation, raises many of the same questions as does use of chemical biocides. In addition, it raises issues of locating equipment on-board and treating very high flow rates of ballast water.

In addition to chemical or physical treatment during ballasting or deballasting, a limited range of treatments may be effective inside ballast tanks. These include heat treatment to a temperature that will inactivate target organisms and chemical addition directly to tanks. In addition to most of the questions described above, these technologies require pilot and full-scale testing to demonstrate that they can be effective in real ballast tanks and with realistic conditions of ship operations.

Separation technologies

Separation technologies have often been proposed for ballast water treatment, including vortex (centrifugal) separation, microscreens, membrane filters and granular bed filters. Some of the approaches seem severely limited in their ability to remove all organisms of concern, because of their small size or small density difference between the organisms and BW. The others pose a range of issues that need study. All need specification of measures of treatment efficacy and criteria for removal efficiency. The IMO performance standard , however, will direct guide development toward nearly complete removal of larger (>50 µm) organisms with much less stringent removal of smaller plankton. Membrane systems are desirable because they can be compact, but development of higher flux membranes, possibly with larger pore sizes (e.g. 50 µm to meet the IMO standard), may be needed for feasible ship board use. Deep, granular media filters may be operated at very high filtration rates and can effectively remove organisms, but removal depends strongly on size and shape of the organisms. Use of granular bed filters for BW treatment will be fundamentally different from applications in drinking water. Particle removal mechanisms will not be dominated by chemical destabilization and agglomeration of colloidal particles, but rather will apparently depend on mechanical straining or capture in interstitial pores in the granular media. Fundamental and developmental research is needed for these technologies.

A Research Program

The current research program in the US was described, at least in part, to the workshop, and it seems inadequate to the challenge of BW discharge control. It has not been funded consistently, nor adequately; it may not have sufficient input from all stakeholders and from the research community and, hence, may not have the correct prioritization of needed research; it has little ability to support knowledge-driven projects that seem needed to address many of the complex scientific issues that underlie the technological approaches.

BW discharge control is an international problem, involving adverse impacts in ports in most maritime nations and necessitating solutions that can be adopted globally, so engineering solutions need to be developed that meet US needs and that are consistent with the IMO

convention. At a minimum, research in the US needs to be communicated freely and frequently with the international community. Optimally, much of the BW discharge control research should be coordinated with efforts in other nations.

Much of the research needed to understand and develop BW discharge control is fundamental. Experience has shown that the best mechanism for rapid progress is investigator-initiated, knowledge-driven and peer-reviewed research awards. The NSF has been the strongest supporter for this kind of research in the US and is well positioned to contribute to effective BWDC. Investigators should be encouraged to submit proposals to appropriate divisions and programs within NSF, certainly including, but not limited to, Environmental Engineering of the Bioengineering and Environmental Systems Division.

Another major part of the research can be prioritized and defined by scientists, engineers and other stakeholders in BW management. A research program can be developed, projects defined, Requests-for-Proposals published, and research contracts awarded based on competitive proposals. AWWARF provides an excellent model for a research program that incorporates the judgment of the major stakeholders about key, researchable issues in the drinking water industry and develops prioritized research programs extending over several years. Their project definition and research contracting process has been effective in engaging the research community and producing useful scientific and developmental research. With some modifications (notably to avoid excessive operational control of research-in-progress), it could be adapted to the broader government supported research effort in BW discharge control, especially if increased funding was available to support a program of sufficient scope to address the problem.

The need for research extends well beyond the range of traditional NSF research grants, and the need for funding well beyond the resources of NSF programs that may relate to BW discharge control research. NSF has had many successful programs in partnership with other agencies, such as the Environmental Protection Agency and the National Oceanic and Atmospheric Administration, as well as with international agencies. These may provide a useful model for BW discharge control research. Funding by the maritime industry also may be needed, either through voluntary contributions or as part of port fees. Creative and cooperative effort is needed by all the stakeholders in the issues of BW and ANS in order to solve the difficult problems that lie ahead.