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ABSTRACT: By provision of the National Invasive Species Act of 1996 (P.L. 104-332), the U.S. Coast Guard and the Smithsonian Environmental Research Center were directed to create the National Ballast Water Information Clearinghouse. A primary charge of the Clearinghouse is to measure patterns of ballast water delivery and exchange across commercial shipping ports throughout the United States. The Clearinghouse has implemented the National Ballast Survey (NABS) to investigate these patterns. NABS is designed explicitly to measure patterns of ballast water delivery and management (primarily ballast water exchange) according to vessel class by geographic region and season of arrival. Additionally, among-year changes in ballast water management by vessel class and geographic region will also be possible. An important aspect of NABS is the ability to assess accuracy of data through use of multiple, independent data sources. In 2001, data from the Clearinghouse will be analyzed and reported to the U.S. Congress and U.S. Coast Guard for review.

Key words: National Ballast Survey, ballast water, exchange, management

INTRODUCTION

The National Invasive Species Act of 1996 (NISA) directed the U.S. Coast Guard (USCG), in conjunction with the Smithsonian Environmental Research Center (SERC), to develop a National Ballast Water Information Clearinghouse (hereafter Clearinghouse). The Clearinghouse, located at SERC, plays a central role in the organization and analysis of national data concerning the transfer and invasion of nonindigenous species associated with the ballast water of ships.

The Clearinghouse serves as a source of national information on ballast water and invasion biology. The primary foci of the Clearinghouse are (1) the study of spatial and temporal patterns of ballast delivery and management, (2) the study of patterns and rates of nonindigenous species invasion, (3) a directory of ongoing and past research in these areas, and (4) compilation of the broad range of general topics relevant to these issues. Synthesis of these data will provide a valuable resource, which is now lacking, and will be accessible via a Clearinghouse site on the World Wide Web (http://invasions.si.edu/ballast.htm). Such a synthesis will promote comparisons between patterns of invasion and patterns of ballast water management, and testing for a reduction of invasion rate in response to various management activities.

NISA calls for a variety of measures to reduce the risk of exotic species invasions associated with release of ballast water by ships. Among these, NISA requests that all ships arriving to U.S. ports from outside the Exclusive Economic Zone (EEZ) follow voluntary guidelines for open-ocean exchange of ballast tanks that are to be discharged in U.S. waters. This management practice is intended to "flush out" ballast tanks and minimize the transfer of nonindigenous coastal species.

A key element of NISA involves tracking the effectiveness of voluntary guidelines, as measured by (1) the level of compliance with voluntary guidelines, (2) changes in the rate and patterns of ballast water delivery, and (3) reduction in the rate of ballast-mediated invasions. The Clearinghouse was created to provide these analyses on a national scale.

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The Clearinghouse has developed a nationwide program to measure the current and changing patterns of ballast water delivery to U.S. ports. This program, called the National Ballast Survey (hereafter NABS), estimates the amount and source of ballast water discarded by commercial vessels and originating from outside of the nation’s EEZ.

This program will result in a comprehensive analysis and biennial report to the U.S. Congress on the status of ballast water delivery throughout the country. The first report will provide a national baseline of information on current status, and subsequent biennial reports will measure trends or changes in ballast water management.

**METHODS**

The overall objective of NABS is to measure the spatial and temporal pattern of ballast water delivery to U.S. ports from all commercial vessels arriving from outside of the EEZ. In particular, NABS measures ballast water delivery and management (including exchange) by vessel class, geographic region, season, and year; characterizes ballast water exchange according to type and degree of exchange; and provides verification of data through use of multiple, independent data sources. Specifically relevant to NISA, NABS estimates (1) the frequency of voluntary compliance with ballast water exchange guidelines authorized under NISA and (2) the effects of compliance on the pattern and rate of ballast water delivery.

Although these objectives are conceptually straightforward, there are many complexities to address in the design of NABS. One such complication involves widespread variation among

- vessel types—There are many different classes of commercial vessels, which can differ in both the ballast water delivery pattern and management (i.e., exchange) practices;
- geographic regions—The use of ballast water may differ among regions, even when controlling for vessel type, depending upon cargo, port system characteristics, prevailing weather, and other factors;
- seasons—The use of ballast water may vary by season, even when controlling for vessel type (e.g., due to weather);
- years—The use of ballast water may change among
years, especially reflecting long-term changes in rate of management practices such as ballast water exchange.

The diverse array of ballast water tanks within a single vessel also poses a challenge to describing ballast water management patterns. Each tank may have a different history with respect to its ballast water sources and management. Furthermore, ballast water exchange can occur in two different ways (empty-refill or flow-through) and to various degrees (e.g., 50% replacement, 200% replacement of the original water).

A particularly difficult issue in describing water delivery and management involves the extent of error associated with data reporting. There are two potential sources of error: (1) error due to under-reporting by ships, and (2) the accuracy of the data that are reported. NABS is designed to estimate both types of error.

To meet the objectives outlined above, NABS is designed explicitly to describe national ballast water delivery and management patterns on multiple spatial and temporal scales. More specifically, a stratified design for data collection and analysis has been implemented and is described below.

Analytical Strata: Vessel Type, Geographic Region, Season, and Year

It is probable that ballast water management (such as the frequency of exchange) varies according to vessel class, geographic region, and season. NISA allows for implementation of regulations of ballast water exchange on any one of these strata. NABS therefore provides resolution at each of these levels to evaluate where voluntary guidelines are or are not effective.

Although NABS is intended to establish an important baseline of ballast management practices during its first two years (i.e., subject of the first report to the U.S. Congress), it is important to recognize this as a “snapshot” measure of patterns. Because the frequency of ballast water exchange may change over time, NABS is designed to evaluate both current practices and long-term (i.e., among-year) trends in ballast water management.

Vessel Type

There are several classes of vessel that arrive at U.S. ports from outside of the EEZ (e.g., tankers, bulk carriers, container ships, general cargo vessels). These vessel types are designed to transport particular types of cargo and vary in size and ballast water capacity. The type of cargo, size, and ballast tank configuration can influence not only the quantity of ballast water released in a port, but also the overall management of ballast, including the history of ballast water and whether ballast water exchange is conducted (e.g., NRC 1996).

NABS will collect data necessary to (1) characterize the ballast water delivery and management pattern for each major vessel class and (2) compare directly the amount of released ballast water and the history of this water (i.e., ballast water sources and frequency of ballast exchange) among vessel classes.

Geographic Region

The coastal United States and its ports can be variously divided into distinct geographic regions. Each area differs in the amount and sources of ballast water received from commercial vessels (Carlton et al. 1995). Spatial differences in ballast water characteristics can result from differences in the overall number of ships, the relative abundance of different vessel types (as above), and the management practices employed. Importantly, ballast management practices (such as the amount of ballast water on board or the frequency of ballast water exchange) may vary spatially, even controlling for vessel type, depending upon weather conditions, import-export patterns, or other factors.

NABS tests for spatial patterns in the delivery and management of ballast water. Although there are many spatial scales to consider, the U.S. Coast Guard Captain of the Port (COTP) zone has been chosen as the level of spatial resolution for analyses. There are approximately 32 COTP zones in the United States (Figure 1). Each COTP zone is comprised of multiple ports and is headquartered at one of these ports. The selection of the COTP zone as the spatial scale of resolution has distinct advantages for the organization and management of data collection. More specifically, this plan allows NABS to take full advantage of the existing structure of U.S. Coast Guard operations throughout the country to obtain and disperse information about commercial shipping and ballast water.

Season and Year

The use of ballast water, as well as the capacity of vessels to safely conduct ballast water exchange, may vary temporally. First, weather patterns or cargo
(import-export schedules) may influence ballast water management on a seasonal timescale. Second, ballast water management patterns may change across years, controlling for seasonal variation. Such interannual changes may result from shifts in trade patterns as well as implementation of NISA's voluntary guidelines or from other future management programs.

NABS will test for temporal patterns among seasons and years. Furthermore, because temporal patterns may vary (interact statistically) with vessel type and geographic region, it is essential to examine temporal data within each COTP zone and vessel class (as outlined above). NABS employs this scheme to provide a comprehensive analysis of nationwide patterns, including the necessary resolution to examine the individual influences of vessel class, geographic region, and season. Furthermore, a comparison among years will be obtained for each major vessel class by controlling for seasonal patterns.

Characterization of Ballast Water Exchange and Delivery

Although vessels often carry ballast water that derives from multiple sources, NABS is designed to provide a clear accounting only for ballast water that (1) originates outside the U.S. EEZ and (2) is discharged within U.S. waters, corresponding directly to NISA's voluntary ballast management guidelines. Information on the history of ballast water in other tanks may also be of interest and relevant to invasion management. For example, relatively empty ballast tanks may carry some risk of invasion associated with residual organisms that can occur in both sediments and biofilms and thus be resuspended and discharged following entry into U.S. ports. In addition, water from domestic U.S. ports may promote the spread of nonindigenous species after initial invasions. However, these elements are beyond the present scope of NISA and NABS, and the associated risk is less well defined than that of ballast water from foreign sources (hereafter foreign ballast water).

NABS estimates the total volume of foreign ballast water released in U.S. waters, characterizes the history (origin, management, and fate) of this water, and identifies specific information about ship and voyage characteristics. A tank-by-tank history for all ballast to be released per ship is collected for analysis. This history includes the origin of ballast water, whether open-ocean exchange or some other ballast management practice occurred, type of exchange (i.e., empty-refill or flow-through), degree of exchange (i.e., percent of water replaced), and location of exchange. It is biologically significant to distinguish between an exchange of 50% vs. 200% of the ballast water in a tank, because these differ in the efficiency of removing unwanted organisms (i.e., not all ballast water exchange is of equal value in reducing nonindigenous species transfer).

Verification of Data through Use of Multiple, Independent Data Sources

The success of NABS in accurately assessing current ballast water practices, and complying with voluntary guidelines under NISA, depends upon the quantity and quality of data. Three characteristics of paramount importance in making inferences include:

- accuracy of the data (i.e., error in measurements);
- use of data that are representative (i.e., randomly selected and independent measures);
- sufficient data to provide adequate estimates (i.e., reasonable statistical confidence).

NABS utilizes multiple sources to obtain accurate and representative data for analyses (Figure 2). This can be viewed as a multi-step process, involving three primary data sets, although others may become available as state and regional ballast water legislation and efforts emerge. First, the data submitted directly by the vessels upon arrival to the United States includes ballast water history for most vessels arriving at each U.S. port from outside of the EEZ (i.e., Ballast Water Reporting Forms, hereafter BWR forms). Second, a

Figure 2. Functional aspects of the United States National Ballast Survey (NABS). Data from multiple sources are entered into the Clearinghouse database, queried, and analyzed to determine ballast management patterns.
comprehensive data set that includes all arrivals at each port (U.S. Customs data as reported by the Maritime Administration, hereafter MARAD data) determines the proportion of vessels that do not submit BWR Forms (i.e., rate of under-reporting). Third, a subset of all arrivals will be boarded by the U.S. Coast Guard to (1) estimate the accuracy of the BWR forms data and (2) make statistical comparisons of ballast delivery patterns by vessel class, geographic region of origin and arrival, and size. These latter data are obtained by the U.S. Coast Guard via a stratified random selection and survey of vessels arriving in U.S. Coast Guard COTP zones.

**Data Sources and Types**

The quantity and nature of data vary among sources, and each is intended to serve a specific purpose.

**BWR Forms**

The most comprehensive data on ballast water delivery and management come from the BWR forms. All commercial vessels entering U.S. waters from outside of the EEZ are expected to report to the Clearinghouse specific information concerning ship and voyage characteristics, ballast water history, and ballast water exchange. Assuming a high rate of reporting and accuracy, the BWR forms will (1) provide a dataset of up to 50,000 ships per year for all major commercial vessel types and U.S. ports and (2) be used as a primary dataset for analyses of nationwide patterns.

**MARAD Arrivals Information**

MARAD organizes a complete record on arrival of commercial vessels to U.S. ports. For each ship, MARAD records data on vessel type as well as other ship and voyage characteristics. These data are used to measure the rate of under-reporting associated with the BWR forms. Through direct comparison of the two data sets, the number and identity of ships (by vessel type, port, and date) absent from the BWR database can be calculated.

**U.S. Coast Guard Survey**

The U.S. Coast Guard provides data for multiple vessel classes by region (COTP zone) and season. These data are collected from randomly selected vessels and include ballast water history, ballast water management, and ship/voyage characteristics. In addition, a water sample is taken from exchanged tanks and analyzed for salinity content. The Clearinghouse is currently convening a workshop to explore other analyses to differentiate coastal from open-ocean water. These data are used to estimate the error rate in the BWR Forms, providing a measure of accuracy.

There is intentional overlap in the information included in the BWR form and U.S. Coast Guard survey, providing a direct comparison to check for accuracy (errors) of the BWR Forms. This survey also creates the opportunity for U.S. Coast Guard to communicate directly with ship operators, to clarify ships' practices (as represented on the BWR forms), and to address questions that may exist about the voluntary program.

**Additional Surveys**

There are several opportunities to obtain additional data through other surveys to augment the U.S. Coast Guard survey effort and provide a complementary, independent set of measures. For example, (1) SERC and other research institutions may collect data on ballast water characteristics, (2) some state, regional, and local agencies have expressed an interest in particular types of ballast water measurements, and (3) some agencies may be willing to assist in short-term, intensive measures of ballast water (e.g., “Ballast-Water Awareness Month”). Development of these opportunities is now being pursued actively.

**Data Management**

A central feature of NABS is a relational database where all ballast water information is stored and managed. The management and use of data from each source can be viewed as a series of step-wise processes that involve this database. Key steps include data receipt, data entry, data validation and proofing, database queries, and statistical analyses. In addition, data management requires some regular, iterative steps involving maintenance and security.

**Data Receipt**

BWR Forms. Most BWR Forms are currently sent to the Clearinghouse by fax and U.S. mail. Faxes and mailed forms are catalogued, photocopied, and archived in separate physical locations for security purposes. Data are entered manually into the Clearinghouse database and undergo validation during this
process. Entered data are then proofread against original hard copies to check for entry errors.

The Clearinghouse also provides several systems for electronic and remote reception of completed BWR forms. These systems include a BWR form posted on the World Wide Web (http://www.serc.si.edu/invasions/ballast.htm), e-mail transfer of forms as attached files (ballast@serc.si.edu), and forms sent directly on disk. Forms in any of the electronic formats are checked visually for formatting errors and proofed before import into the Clearinghouse database.

MARAD Arrival Information. The MARAD data on nationwide arrivals are transferred electronically to the Clearinghouse. As above, these data are checked visually for formatting errors.

U.S. Coast Guard Survey. Data from the U.S. Coast Guard survey are collected on handheld computers or hard-copy questionnaires. Data are uploaded to District Coast Guard computers and transferred to the Clearinghouse database via modem or the Internet. Hard copies of all data files are printed, examined for format or transmission errors, and archived at SERC.

Analyses

NABS employs a variety of analyses to address questions about nationwide ballast water delivery and management patterns. The multiple data sources are queried to estimate independent estimates of ship arrivals and ballast water delivery by vessel class, geographic region, season, and year. A comparison of results among data sources allows NABS to estimate error (i.e., statistical confidence) in the results from the BWR forms due to (1) inaccuracy of reported data, (2) the rate of under-reporting, and (3) potential biases associated with under-reporting. Furthermore, through analysis of these multiple data sources, NABS can report patterns of ballast water delivery that include estimates of statistical confidence as well as statistical comparisons among strata.

Analysis of BWR Form data

If all ships submitted error-free BWR forms, determining the patterns of ballast water delivery and management would be a simple task of data tabulation. In reality, not all ships submit a BWR form and errors exist among forms that are submitted. To address these problems, NABS estimates the magnitude of uncertainty due to under-reporting and calculates inaccuracy of the BWR form data. NABS uses the BWR form data to measure broadscale patterns and other supporting data sets to estimate the associated error. Error estimates come from comparisons with MARAD data (to measure under-reporting) and U.S. Coast Guard survey data (to measure data accuracy). These estimates of error are used to generate confidence intervals around BWR form data mean estimates. Given the sample size (i.e., 32 COTP zones and 3840 samples per year nationally) this approach should be highly effective for estimation of ballast delivery patterns on a national basis.

NABS will also report the summaries of all data from the BWR forms by stratum (i.e., vessel class x COTP zone x season). However, it may not be effective to estimate error rates for BWR form data in each of the strata, using identical methods. Unlike the error estimates for national patterns, the degrees of freedom for within-stratum estimates are relatively small and limited to the number of vessels sampled by the U.S. Coast Guard and others. The U.S. Coast Guard Survey data may be more effectively used to directly estimate within-strata compliance and error rates in some cases. Importantly, this latter approach allows for more sophisticated statistical comparison of ballast characteristics among strata.

Error Due to Inaccuracy

To estimate error due to inaccuracy, the results of the U.S. Coast Guard survey are compared directly with BWR form data. Specifically, the inaccuracy is treated as the result of two random events: (1) whether a mistake was made and (2) the magnitude of the mistake. Event 1 can be modeled as a binomial random variable. If no mistake was made, the inaccuracy is zero. If a mistake exists, the second random variable is the magnitude of this mistake and can be modeled using a normal distribution. The results of this model can generate error estimates for the tabulated results of the BWR forms.

Analysis of data from U.S. Coast Guard Survey

Although data from the U.S. Coast Guard survey play a key role in analyzing BWR forms data (as above), they also provide a valuable tool for fine-grained analyses and comparisons of ballast water characteristics. For example, these data can be used to test for statistical differences in the amount of unexchanged ballast water (or rate of compliance) for bulkers versus tankers between two regions, whereas
the potential for such direct statistical comparisons will be more limited with the BWR form data.

NABS uses standard parametric and non-parametric statistical techniques to test for differences in ballast characteristics among strata. For continuous data, multi-factor or nested ANOVA with multiple comparison of means are used. For dichotomous or categorical data, logistic regression and log-linear analyses are used. To test for long-term trends, ANOVA and linear regression to compare ballast characteristics among-years are employed.

**INITIAL RESULTS AND DISCUSSION**

Although data collection began on July 1, 1999, it is still too early to publish definitive results. Data collection is planned for an additional 18 months, until at least summer 2001, at which point full scale analyses will be performed. The results from this program will be included in a congressional report prepared by the Smithsonian and U.S. Coast Guard. In the interim, the Clearinghouse is posting quarterly reports on the World Wide Web (http://invasions.si.edu/ballast.htm).

Some apparent, but preliminary, trends are beginning to emerge based on the data collected to date. It must be noted that data collected so far only span two and one-half seasons, thus no seasonal or inter-annual variation can be described. Given the extent of this national program and the temporal proximity to its start date, it is premature to assess whether participation by commercial ships will change through time.

The Clearinghouse has received approximately 10,600 BWR forms from July 1, 1999 through January 31, 2000. This equates to 1,515 forms per month. Figure 3 tracks the number of forms received per week. The slope of the curve is constant, indicating an unchanging influx of BWR forms of 51 forms per day. At this rate, the total number of forms expected for 1 year is 18,400. Assuming no seasonal variation, the constant rate of arrivals across 7 months implies no change to the number of participants in the program. As more commercial vessels learn of the reporting requirement, an increased reporting rate is to be expected, but the current findings suggest little or no change to ballast water management and delivery reporting.

Based on MARAD data from 1996 through 1998, the number of commercial vessels (greater than 300 gross tons and excluding passenger vessels) that arrive
per year is approximately 50,000, with very little inter-annual variation. Although the Clearinghouse does not yet possess MARAD data corresponding to the exact dates of the NABS data collection, precluding direct comparison, it appears there is substantial under-reporting on the part of commercial vessels. If MARAD data from recent years is a good indicator of recent vessel arrivals, approximately 40% of the vessels required by NISA to report their ballast water management and delivery practices are doing so (i.e., 60% under-reporting). As stated earlier, the degree of under-reporting reported here must be verified by comparison with MARAD data that are contemporary to the period in question.

Because of the apparent extent of under-reporting to date, the Clearinghouse is undertaking additional analyses (1) to confirm this result and (2) identify the source of under-reporting by region and vessel type. A first step in this process, now underway, is to verify that the MARAD data do not overestimate arrivals. Following any corrections, if necessary, the second step will identify the extent of under-reporting by geographic region, vessel type, and season.

At present, little can be said with respect to spatial variation among and within coasts. A similar situation exists for comparisons among vessel types, and for analyses to detect temporal variation. As more data are compiled, the resolution at which analyses and comparisons can be made will increase and patterns will begin to emerge. In the long run, it is hoped that data on shipping and ballast management and delivery will be useful to those engaged in efforts to describe the rate and pattern of marine invasions to U.S. waters.

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An International Exchange of Ballast Water Research between New Zealand and Massachusetts

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Abstract: Research on the ballast water problem in New Zealand since 1995 is briefly described, including the results of a two-year sampling survey of container ships and bulk carriers in the ports of Lyttelton and Nelson. Current research involving both the Cawthron Institute in New Zealand and Battelle in Massachusetts, is looking at methods of measuring the water volumes exchanged by ships in mid-ocean (by reballasting and by dilution) and the efficiency of these exchanges in ridding tanks of unwanted species. The research also includes existing and potential methods that may be used by quarantine agencies to confirm independently that mid-ocean exchanges have occurred. Other research by Cawthron is investigating the survivorship of species in ballast tanks in greater detail, particularly on trans-Tasman Sea and trans-Pacific voyages.

Keywords: ballast water, exchange, efficiency, compliance, indicator, New Zealand, plankton

Introduction

The undesirable dispersal of marine organisms in ships’ ballast water is, by nature, an international problem. In the last 10-15 years, as this environmental problem has become increasingly apparent, various maritime nations have commissioned reviews and enquiries and held national and international meetings on the subject. The International Maritime Organization (IMO) of the United Nations is involved, particularly through its Marine Environment Protection Committee (MEPC) and its Convention for the Prevention of Pollution from Ships (MARPOL). Mandatory international regulations for managing ships’ ballast water are imminent, and already apply inside territorial sea areas of some maritime nations and within the jurisdiction of some ports.

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When funding for research on the ballast water problem is provided, the scope is often regional, with the funds coming from ports, or local or state government. Few nations have any significant, long-term, nationally funded research programs on the ballast water problem. There are also very few instances of international collaboration, except perhaps in the Great Lakes where geography compels the involvement of neighboring nations.

This paper briefly describes how ballast water research carried out by the Cawthron Institute in Nelson, New Zealand, over the last four years evolved into a collaborative research program with Battelle Ocean Sciences, Duxbury, Massachusetts.

New Zealand is a small, geographically isolated, sparsely populated (3.7 million in 1996) island nation with a disproportionately long coastline relative to its land area. Like our much larger Australian neighbor, from whom we are separated by the 1000-mile-
wide Tasman Sea, agriculture, forestry, minerals, and fisheries are important exports. Generally, these have very much higher volume-to-value ratios than do New Zealand’s less bulky imports. Most of the 2,500 to 3,000 trading vessel visits to New Zealand each year are by ships that are fully or partly ballasted. With the exception of bulk carriers importing petroleum products and fertilizers, most bulk carriers arriving in New Zealand are fully ballasted. Collectively, all types of vessels discharge an estimated 4 to 6 million mt of ballast water annually. The Australian ports receive an estimated 150 million mt.

As is described by Taylor et al. (2000) in this volume, more than half of New Zealand’s trade is with Asia and Australia. Several of the conspicuous non-indigenous species that have arrived recently are of Asian origin and are also established in Australia; e.g., the Asian kelp, Undaria pinnatifida, and the Asian date mussel, Musculista senhousia (Furlani 1996). Considerable trans-Tasman trade between New Zealand and Australia means that foreign invaders on temperate shores of either country are likely to be translocated by shipping across the Tasman Sea.

New Zealand government funding for research on the ballast water problem has been made available in the last four years, and was perhaps partly prompted by a notable conference Ballast Water—A Marine Cocktail on the Move held by the NZ Royal Society in Wellington in 1995 (Lynch 1995). In 1996, the New Zealand Ministry of Fisheries (MFish) [previously part of the Ministry of Agriculture and Fisheries (MAF)] funded the Cawthron Institute to conduct research on ballast water with these goals: (1) to devise a method for routinely sampling ballast water from a wide range of ship types and (2) to examine the samples microscopically to compare the biota with such variables as (a) age of the water, (b) the size and types of tanks and ships, and (c) whether or not the ships had claimed to have exchanged their ballast water in mid-ocean.

The Quarantine Problem: Identifying Non-compliant Vessels

Quarantine agencies responsible for enforcing national regulations pertaining to discharges of ships’ ballast water, e.g., MFish or the Australian Quarantine Inspection Service (AQIS), need to identify noncompliant vessels. These are vessels that have not made mid-ocean exchanges in accordance with IMO recommendations, which, briefly stated, are that vessels exchange ballast in deep water (not shallower than 500 m) far from coastal influences, by emptying their tanks until suction is lost before reballasting, or, in the case of flow-through dilution, by pumping a volume of mid-ocean water equal to at least three times the vessel’s ballasting capacity.

Port companies also may increasingly have vested interests in identifying vessels that constitute a quarantine risk. A Contra Costa Times reporter, Denis Cuff, reported that the Marine Conservation Center and Baykeeper organizations of San Francisco had notified the Port of Oakland, on 7 January 1999, of their intention to sue the Port for alleged insufficient measures to control and prevent the arrival of invasive species in ships’ ballast water, thus harming San Francisco Bay fish and aquatic life. According to Michael Lozeau, executive director of the San Francisco Baykeeper, “Ocean exchange of ballast is a good interim step, but is not the final answer [to the problem]” (Contra Costa Times 9 January 1999).

As a quarantine measure to minimize the risk of dispersing invasive marine and freshwater species, the efficacy of exchanging ballast in mid-ocean is perhaps based more on intuitive common sense than upon hard scientific evidence. Scientists were advocating such a procedure at least a decade ago; e.g., Williams et al. (1988). In the case of exchanges made by emptying and refilling tanks, the removal of most of the water must, arguably, greatly reduce the risk of introducing nonindigenous species—although there remains the nagging uncertainty about residual water and sediments that cannot be voided before refilling begins.

The efficacy of flow-through dilution, by pumping through a volume three times that of a ship’s ballasting capacity is, however, less intuitive. The procedure is recommended by the IMO partly on the basis of pioneering Australian work undertaken by Drs. Geoff Rigby and Gustaaf Hallegeraeff (1994) on the 141,475 dwt BHP Bulk Carrier M.V. Iron Whyalla in September 1991 (when the vessel was at anchor at Singapore) and in July 1992 on a voyage from Japan to British Columbia (AQIS 1993, Parts 1 and 2).

For both trials, methylene blue was used as a tracer to measure the dilution of the original water, and changes in the diversity and the abundance of phytoplankton during and after the exchange were recorded. Rigby and Hallegeraeff (1994) concluded that pumping through three times the capacity of ballast tanks effectively diluted the original water.
There were some problems with these trials, however, notably that the dye could not be evenly dispersed inside the tanks before the exchange took place, and significant differences in initial concentrations at sampling points before the exchange indicated plug flow. Also, methylene blue stains living plankton in addition to remaining in solution. So there was the potential problem of differentiating between dilution by adsorption onto organisms and that caused by the diluting effect of the incoming water.

The flow-through of three times capacity to achieve 95% dilution is also identical with the theoretical figure derived from an exponential decay equation familiar to water engineers involved with dilution dynamics. It assumes instant and perfect mixing. The complicated internal structure of some ships’ ballast tanks, often a labyrinth of smaller compartments and baffles, is, however, far removed from any perfect mixing container (Figure 1).

**Ballast Water Research by Cawthron Before 1998**

Between October 1995 and October 1997, scientists at the Cawthron Institute examined over 160 ballast tanks of all types on 75 vessels in the ports of Lyttelton and Nelson. Their procedures and the results of the water analyses are given in Hay et al. (1997).

On the basis of ships’ records, the water from the forepeak, afterpeak, upper wing, and lower wing tanks and from the ballast holds that were sampled, was, on average, less than 10 da old. In deep tanks, the average age of the water was 20 da; while in double-bottom tanks the average was 40 da. The oldest water sampled, which was in a double-bottom tank, was reported to be 494 da old.

**Sampling methods**

Several water sampling methods were tried. An electric Waterra Hydrolift II inertia type pump (Waterra Ltd., 77 Mowat Ave., Suite 101, Toronto, Ontario) proved to be the most reliable water-lifting device, and ensured fast, routine sampling on any vessel with sounding pipes (more than 90% of the ships boarded had sounding pipes). Coils of 12-mm or 20-mm diam. semi-rigid, black polythene plumbing pipe, about 25-m long, were used to conduct ballast water up to the weather deck of the ship from tanks as low as 22 m below deck level. A brass or nylon foot valve (a non-return valve) was inserted into one end of the pipe coil. That end was pushed down the sounding pipe until the bottom of the tank was touched. The plastic pipe was then slightly withdrawn (about 50 cm) to prevent the valve from striking the tank bottom when the pump was in action. The Waterra pump, which has an adjustable arm that moves vertically up and down, was placed with the arm directly above the sounding pipe from which the polythene pipe was protruding. The arm was then tightly clamped to the polythene pipe just above deck level, and the pump was started. The speed of the motor and the stroke of the arm were adjusted to ensure a steady pulsing flow of water, typically 3-6 L/min. (It helps to first prime the pipe by vigorously jerking the pipe up and down manually for a few minutes before clamping the pipe to the pump arm.) By this method, we obtained 100 L water samples from all types of tanks within 15-30 min. We ran the pump by tapping into the ship’s power via reefer sockets, or by using the power sockets for cranes, winches, or deck lighting. Several custom-made transformers and an array of adapters and plug types were needed to make the necessary power connections. To sample tanks less than about 6 m below deck level, we initially used petrol and electric impeller (centrifugal) pumps. Although these pumps are faster, they are more vigorous, and damaged some plankton species that were apparently undamaged by the slower inertia pump. In general, the samples obtained by using the inertia pump had a slightly wider taxonomic range of species (see Hay et al. 1997, fig 3.3). We therefore preferentially used the inertia pump.
unless time constraints necessitated using the faster centrifugal pumps.

Results

Phytoplankton

Eighty percent of the tanks sampled contained live phytoplankton, with diatoms being the most common, followed by heterotrophic flagellates and dinoflagellates. The diversity and abundance of live phytoplankton was proportionately greater in the tanks of bulk carriers and break bulk carriers than in the tanks of container ships. Live phytoplankton were least frequent and often absent in the double-bottom tanks, especially in container ships. Presumably, this was because these tanks are used primarily for stability, and, compared with other tanks such as upper wing tanks, are infrequently emptied and refilled.

The tanks containing the highest diversity of the major phytoplankton groups were those that reportedly had been exchanged en route to New Zealand (Figure 2). This suggested that the exchange added live oceanic species belonging to groups that had previously declined or died in the darkness.

Invertebrates

Live invertebrates were found in 83% of all tanks sampled. Crustaceans were most numerous, being recorded in 80% of the tanks. Live mollusks were found in 27% of the tanks and annelid worms in 15% of the tanks (Figure 2). Compared with phytoplankton, invertebrates were proportionately more common (by 10%) inside the tanks of container ships. As with phytoplankton, the double-bottom tanks had the lowest proportion of living invertebrates. Upper wing tanks, forecast tanks, and particularly ballasting holds contained the most live invertebrates.

There were slight differences between exchanged and nonexchanged tanks with respect to the diversity and abundance of some invertebrates (see Figure 2). Coastal harpacticoid copepods were nine times more common inside tanks that had not made a mid-ocean exchange. Certain groups of annelids, such as the Ophelioidae and Phyllodoceidae, were not represented in tanks reportedly exchanged in mid-ocean. In general, however, the diversity and abundance of invertebrates was similar in both exchanged and nonexchanged tanks. The larvae of predominantly coastal mytiloid and veneroid bivalves occurred about equal-

Figure 2. Percentage of tanks containing phytoplankton groups and zooplankton (including other invertebrates) phyla in exchanged and nonexchanged tanks, from Cawthron’s 1995-97 ballast water sampling program.

ly in both exchanged and nonexchanged tanks. Yet, theoretically, the larvae of these groups should be much lower or absent from the tanks purportedly carrying mid-ocean water.

These data suggest that in many cases the exchange procedure did not eliminate coastal species. For some taxonomic groups, recently settled juveniles may have persisted in sediments that are unlikely to be removed by mid-ocean exchange. The presence of recently metamorphosed juvenile annelid worms and juvenile mollusks also indicated the presence of semi-permanent resident populations within the sediments. These sediment-dwelling organisms may in fact be nourished and revitalized by fresh injections of mid-ocean water during exchanges.

The high percentage of coastal and oceanic species that survived suggests that any vessel discharging foreign ballast water into New Zealand waters is a significant quarantine risk, unless the ballast it is discharging has been contained by the vessel for several transoceanic voyages. For approximately half of the
samples, data were inconsistent with claims that the water had been exchanged in mid-ocean. This was either because (1) no exchange was made, (2) the exchange was only partial, thus resulting in a mixture of coastal and oceanic water, (3) coastal biota that had been transported to the mid-ocean in currents was uplifted during the exchange, or (4) somehow the biota from previous ballast loads was retained inside the tanks. Similar conclusions have been made by other researchers; e.g., Locke et al. (1991).

Based on these early studies and those of others, Cawthron and Battelle initiated research to evaluate the effectiveness of exchange-at-sea on vessels that followed their normal exchange procedures.

The Cawthron/Battelle Study
(February 1998–June 1999)

The MFish study, comprised three objectives. The first two were essentially desk-top reviews of methods and procedures currently available for measuring the volumes that are actually exchanged during mid-ocean exchanges and of procedures or water properties that might be usefully employed to test compliance. The third objective involved testing such methods and procedures aboard at least two commercial vessels travelling to New Zealand on international shipping routes. The desk-top review, completed in December 1998 (Hay and Tanis 1998), is briefly summarized below. Preliminary results and observations of research pertaining to the third objective, currently underway, are also provided.

Summary of the Literature Review

The literature review (Objectives 1 and 2) concluded that if international regulations were going to be expressed in terms of volumes exchanged, then any methods available to inspectors that enable them to measure independently the volumetric changes are useful for testing compliance. In this regard, a procedure being tested in Australia called the “Newcastle method,” which requires a master to present a ship’s documentation and other logged information to corroborate claims about making exchanges, is a useful method for identifying vessels making inadequate or fraudulent claims.

Of various methods available for measuring the volumes flowing into and out of ballast tanks, magnetic flow meters were considered to have the greatest potential. Theoretically, such flow meters could be attached to the ship’s ballast tanks, so that changes in a ship’s ballast status may be recorded simultaneously with geographic position and time. Such information can be down-loaded to a tamper-proof data logger, which can be remotely interrogated by quarantine agencies. While such “black box” technology is technically feasible, and is used routinely elsewhere (e.g., by oceanographers), the review concluded that the cost of retrofitting such equipment to the world’s fleet—even to just the newer vessels—together with maintenance problems, rendered such technology impractical. Such an approach must also be weighed against the fact that mid-ocean exchange is acknowledged by IMO to be an imperfect and interim procedure until a better solution to the ballast water problem is found.

Indicators

With respect to physical and chemical features in ballast water that may be used to verify the coastal or mid-ocean origins of ballast water, we concluded that in circumstances where quarantine agencies are particularly worried about the discharges of foreign fresh or brackish water, the measurement of salinity was a very useful indicator. For New Zealand, however, where all large commercial ports are on the coast, the introduction of foreign freshwater is a relatively small quarantine risk—unlike Great Lakes ports, for example. Nevertheless, even in New Zealand, salinity is a useful measurements in cases where vessels originally uplifted river or estuarine water and reportedly made an exchange in mid-ocean. So salinity can be used to detect some cases where the exchange was inadequate or where claims are fraudulent.

The review concluded that measuring concentrations of various chemicals in ballast water is limited as a compliance tool simply because of the nonconservative nature of the tanks. Sediments with contaminants such as organic carbon, nutrients, chlorophyll a, and iron will be resuspended as ballast is taken aboard, lifting levels above those that would reasonably be expected for uncontaminated water, while in ballast holds, previous cargoes (e.g., fertilizers or sugar) may be compromising. Measurements of dissolved oxygen and of the oxidation-reduction state of seawater, while helping to build up a profile of the water, were also deemed unsatisfactory as compliance tools. Not enough is known about the rate of decline of dissolved oxygen in ballast tanks and the effects of resuspending sediments and the biota they contain. While low redox potentials may tend to suggest that
waters are anoxic, in practice the concentration of dissolved oxygen may be quite variable. Oemcke and van Leeuwen (1998) found that oxygen-saturated water from a ship’s ballast tank (6.3 mg/L) had a redox potential of 42.7 mV which would normally suggest anoxia given that seawater typically has a value of more than 200 mV. Oxygen is not the only electron acceptor (oxidizing agent) in the ocean. Nitrates can accept electrons and be reduced to ammonia, and sulphates can be reduced to sulphide, while minerals such as iron can be reduced from the ferric (Fe³⁺) to the ferrous (Fe²⁺) state. It can be shown experimentally how the addition of ferrous compounds to water supersaturated with oxygen can cause an immediate decline in redox potential (e.g., from 276 to 27 mV), without depleting dissolved oxygen (Oemcke and van Leeuwen 1998).

Chemical concentrations might become a useful variable in a multivariable check on the probability of whether a particular load of ballast water is a result of reballasting or three-times-flow through dilution. McKeown and Mills (1998) reported that the U.S. Coast Guard (USCG) had chosen nitrate as an indicator of whether or not ships had made mid-ocean exchanges because nitrate concentrations were an order of magnitude lower in the open ocean compared to coastal and inland waters. How useful this variable proves to be as a tool for testing compliance is not yet known. Obviously, if ships have nitrogen-rich sediments in their tanks, and the sediments and bacteria are resuspended during the exchange process, then the usefulness of the test is compromised. Also, vessels may make exchanges beyond the 12 mi-territorial limit in water more than 500 m deep, which is more characteristic of coastal than of open-ocean water, and has, as a result, higher concentrations of nitrate than would be expected from a truly mid-ocean exchange.

Recent research by Hall et al. (1998) in New Zealand does not support the USCG study. On the M.V. Tasman Enterprise, travelling between Devonport, Tasmania and Tauranga, New Zealand, two pairs of previously fully emptied ballast tanks (244 and 239 m³ capacity) were filled by gravity flow with Tasmanian coastal water. The water was sampled and analyzed daily on the voyage. Day-to-day variations in concentrations of nitrate, ammonia, and phosphorus—with no clear trend over time—were found. The concentrations of these nutrients varied between the two tanks (0.9–4.1 µg/L of nitrate nitrogen in one tank and 28–87 µg/L in the other), even though they had been simultaneously filled with the same source water. The authors therefore concluded that previous ballast water in the tanks may be important in determining nutrient concentrations.

**Optical characteristics**

The review concluded that the preliminary results of a feasibility investigation by Battelle into the usefulness of optical characteristics to determine whether an exchange has taken place were extremely promising. Comprehensive worldwide sampling is required. Based on the preliminary results of about 50 coastal and mid-ocean samples, Battelle has recommended that the USCG continue with its technical investigation of the optical methodology and is advising the USCG on future developments. Ideally, research workers should travel a trans-Atlantic or trans-Pacific route, simultaneously sampling both ballast tanks and the open ocean. The ballast tanks should be sampled at regular intervals throughout the balance of the voyage to detect any changes over time. Samples of original harbor water should also be collected for analysis and characterization. This type of sampling along with a diverse sample set of strategically selected coastal and open-ocean water samples will form a strong foundation for the decision algorithm.

Battelle has also recommended to the USCG new instrumentation to permit onboard processing of ballast water. This is envisioned as a self-contained instrument, roughly briefcase size. It will include some type of sampling interface either to bring samples up from the tanks or to probe the tanks for in situ measurements. The instrument should be fully programmed and automated to determine whether the ballast water sample is predominantly ocean or coastal.

The optical methodology and conceptual instrumentation will require some development. However, once developed, it will provide measurement capabilities sufficient to enforce regulatory compliance.

**Field Test of Methods**

The third objective of the Mfilsh study is to measure the biological effectiveness of mid-ocean exchange and to search for any water feature that can be usefully used to differentiate coastal and mid-ocean waters inside the exceedingly nonconservative environment of ships’ ballast tanks. There are three main tasks:
to measure the actual dilution of the original ballast water after mid-ocean exchange;
• to compare this physical dilution with the removal of organisms in the original water;
• to monitor the physical, chemical, and optical properties of the original and replacement water on trans-oceanic voyages with a view to finding one or more that will differentiate the water types.

Although some of this work is similar to the research previously carried out by Rigby and Hallegraeff (1994) on the M.V. Iron Whyalla, we reasoned that such important work warranted repeating on different types of vessels (especially container ships), in different types of tanks, and on different ocean routes.

Dye trials

Preliminary work at Cawthron indicated that the fluorescent water tracer dye Rhodamine WT was well suited as a tracer for measuring the physical dilution of original ballast water after an exchange. In that preliminary study, we measured how fluorescence over a range of rhodamine concentrations from 1 to 0.0001 parts per million (ppm) was affected by such variables as time, salinity, turbidity, the addition of iron II and III compounds, and by the presence of large numbers of phyto- and zooplankton.

These measurements were compared against dilution curves derived by serially diluting rhodamine in 0.45-μm filtered seawater, river water, brackish water (17%), and deionised freshwater. Dye concentrations and water types were triplicated in 250-ml bottles. Fluorescence was measured with a Turner Designs 10-05 Fluorometer (www.turnerdesigns.com).

We decided that a concentration of 1 ppm was probably the most concentrated dye solution that could realistically be used in ballast tanks. Even at this concentration, the dyed ballast, when discharged, would appear faintly pink, while the volumes of dye necessary could be prohibitively expensive (e.g., 10 L of dye in a 10,000 m³ tank). For ballast water work, we would recommend initial concentrations in the range of 10⁻¹ to 10⁻² ppm. A concentration of 10⁻⁴ ppm approaches the limits of resolution of the fluorometer.

Across the concentration range that we tested, there was a linear, log/log response between concentration and fluorescence. The curves for seawater, river water, and deionised water were very similar and not significantly different at the 95% level. Filtering the sea, river, and brackish water samples, which had high concentrations of phyto- and zooplankton, had no effect on fluorescence.

When we added the tracer at concentrations of 10⁻¹ and 10⁻² ppm to dense cultures of phytoplankton (Gymnodinium and Protoceratium), the readings remained consistent over a week and were unaltered by filtering out the organisms at the end of the experiment. We found that the fluorescence of 250-ml samples of the various water types, when stored in amber bottles in the dark, remained constant for up to four weeks. Left in the light, the most dilute solutions began to lose fluorescence after about a week.

Iron trials

Experiments on the effect of iron indicated that at high concentrations of ferric chloride (e.g., 1 mg/L) there was up to a 30% reduction in fluorescence. Ferrous sulphate, however, had a lesser effect. At lower concentrations (e.g., two orders of magnitude less at 1 μg/L), the addition of the iron compounds had no detectable effect on fluorescence. Adding iron filings to seawater to produce a light brown colouration (similar to weak tea) had no significant effect on fluorescence.

Dye trials on ships

On the basis of our preliminary laboratory trials, we concluded retrospectively that rhodamine would have been a suitable ballast water tracer in most of the 160 ballast tanks we had previously examined—especially in those tanks that were routinely filled and emptied. Such frequently filled tanks typically contain clear water, unlike infrequently used tanks, where the water may be either stained bright red by rust or have turned sulphurously black.

Three trials on a New Zealand coastal vessel, M.V. Spirit of Vision, in a forepeak tank with 115 m³ capacity, demonstrated how important it is to ensure that the dye is thoroughly mixed in the tanks, well before any exchange takes place. We found that this was best achieved by adding the dye to the bottom of the tank as filling commenced, and by filling the tank to less than capacity in the first few hours so that water is able to slosh about. Later, by profiling the tank and comparing the fluorescence with the theoretical value for complete mixing, we found that the water tracer dye in the ballast tank was homogeneous.

We found that the dye dilution at the end of each voyage, after a three-times-flow through exchange, as
indicated by declining fluorescence, was in the range of 89-97%—which is indeed close to the theoretical value of 95%. On one voyage, the tracer was diluted 35% at the top of the tank and 95% at the bottom of the tank, which suggested that the two water masses were stratified by the new, incoming ocean water layering above the original harbor water. This stratification persisted until a water volume about twice the capacity of the tank had flowed through. By the time three volumes had flowed through, however, the remaining dye tracer was homogeneously dispersed inside the tank and the stratification had disappeared. On this trial, the concentration of rhodamine declined from 0.12 ppm before the exchange to less than 0.01 ppm at the end of the voyage. We calculated this as indicating 96.7% dilution of the original water.

With respect to the biota, however, we have some interesting preliminary results from the exchange trials on the Spirit of Vision, which are described by Taylor et al. (this volume). Theoretically, a three-times-volume exchange should cause a 95% decline in the density of the indicator taxa uplifted at source. Indicator taxa were defined as phyto- and zooplankton species that did not occur in mid-ocean plankton samples taken at the same time as the exchanges were conducted. On neither of two trials in New Zealand coastal waters did this occur. This is attributed to inadequate mixing between the original and exchanged water volumes, the possibility that the exchange resuspends coastal species that have previously accumulated in tank sediments, and perhaps an ability on the part of some species to move against the flow and thus remain inside the tank. There is also the possibility, however, that some of the indicator taxa were in fact uplifted during mid-ocean exchanges, even though they were not detected in the mid-ocean plankton samples.

In February 1999, our efforts to measure the efficiency in terms of dilution and the biological effectiveness of mid-ocean exchanges were scaled up to 1,400 m³ tanks on a converted parcel chemical carrier, M.T. Iver Stream (170 m length; 32,570 dwt), traveling between Japan and New Zealand. Three-way comparisons of the old and new ballast water and of ambient mid-ocean water at the exchange location were made during flow-through exchanges, and the chemistry, optical properties, and biota of the ballast water were monitored throughout the entire journey.

On the Iver Stream, Rhodamine WT dye concentrate was added to emptied ballast tanks via Butterworth hatches on deck. These hatches permitted us to pour dye concentrate directly into the empty tanks. The amount of dye added was calculated to provide a final concentration of approximately 0.1 ppm when the tanks were filled and the dye was thoroughly mixed. A check for stratification of the dye, which was made by taking samples of the surface, mid (7 m), and bottom (14 m) layers of the tank 24 hr after they were filled, indicated complete mixing.

Mid-ocean exchanges resulted in a dye dilution of greater than 95%. On one exchange, off the mouth of the Sepik River (north coast of Papua New Guinea), the salinity of the incoming water changed from oceanic (34-35 ppt) to slightly brackish (32 ppt), despite the ocean depth at that location being approximately 900 m. A layer of lower salinity water at the top of the tank demonstrated that stratification was occurring during the exchange. After twice the tank capacity had been exchanged, the stratification disappeared. This result suggests that salinity imbalances may be important with respect to the effectiveness of flow-through exchanges, especially if they are incomplete.

On the Iver Stream voyage, coastal and open-ocean water and ballast samples collected for analyses of their optical characteristics demonstrated that the marked reduction in concentration of dye tracer coincided with significant changes in the optical signature. After each exchange, the optical signature of the ballast water shifted from that of typical coastal water to that of oceanic water. This shift was not observed in the control (nonexchanged) tank.

With respect to the biota in the tanks, preliminary results from our monitoring of events on the Iver Stream show that the rate of dilution (as measured by dye dilution and the optical signature) in the exchanged tanks was associated with a similar decline in the abundance of the dominant indicator taxa (as defined above): adult copepods, 95-100%; larval and juvenile polychaetes, 97-100%; dinoflagellates, 97-99.9%. An important consideration, however, was differences in the change in abundance of viable organisms in the control tank during the time the exchanges were made: adult copepods, 14-79%; larval and juvenile polychaetes, 100%; dinoflagellates, 61-77%. For most groups, mortality appeared to increase significantly after five days. This was associated with a warming of the ballast as the vessel entered the tropics, in addition to the other factors.
affecting survival (e.g., oxygen depletion and absence of light). Several taxa, comprising predominantly coastal species (e.g., bivalve and barnacle larvae), were uplifted in relatively high numbers during exchanges.

Conclusions

Dye tracers such as Rhodamine WT reliably measure the dilution efficiency of mid-ocean exchanges, but the logistical constraints of adding the tracer to the tanks before an exchange, especially where sounding pipes are the only feasible access point, means that tracers are unlikely to be useful compliance tools. Their main application is likely to be in calibrating indirect measures of dilution (e.g., optical signatures).

The flow through dilution method of mid-ocean exchange has been shown to have an efficiency in excess of 95%. However, further monitoring of vessels at sea is needed to verify if salinity imbalances are a problem. When making changes in deep water (>500 m), the salinity of the new water relative to the old should be considered as a factor determining the rate at which the old water is diluted during the exchange.

The dilution of phyto- and zooplankton during mid-ocean exchanges appears to be heavily dependent on the flow dynamics and the mixing characteristics in the ballast tanks. The tolerances of the organisms to the tank environment will be a key factor affecting measures of the rate of dilution of the biota. Identifying and quantifying the factors affecting survival is a priority for further research. Therefore, a wide range of phyto- and zooplankton taxa should be used as indicators of the biological efficacy of exchanges. The usefulness of larval invertebrates as indicators is limited, however, because they can occur in both coastal and open ocean water.

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Future Research on Ballast Water Treatment—A Technologist’s View

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Abstract: Since the mid 1980s, an international research effort focused on the development of ballast water treatment options has been steadily increasing. The effort has resulted in the development of a number of management and treatment options that can be applied to ballast water. Ballast water can be treated on-shore, in port, or on shipboard during ballasting, in-transit, or during deballasting. There has been considerable discussion and debate on the merits of the various options; this paper makes a contribution with an assessment of the current treatment technologies and suggestions for further research. To select the most suitable treatment and management options for ballast water requires a well-informed assessment of a wide range of variables. Some can be rejected or refined on the basis of impracticality, impossibility, and proven poor performance. However, to thoroughly assess the options for ballast water treatment and management will require the development of ballast water treatment standards. The setting of standards for treatment will enable the comparison of treatment options on the basis of cost, safety, environmental risk, and efficacy in a way that is not possible in the present environment. Furthermore, the development of standards will influence the direction of ballast water research by placing a focus on the questions that must be answered to set appropriate standards.

Key words: ballast water, treatment, management, standards

Introduction

Research into the treatment of ballast water has gained considerable momentum since the experiments on ballast exchange of Williams et al. in the 1970s (Williams et al. 1988). Laboratory research has been conducted on methods to inactivate a range of organisms, including algal cysts (Oemcke 1999a; Hallegraeff et al. 1997; Montani et al. 1995; Bolch and Hallegraeff 1993; Ichikawa et al. 1992), other algae (Oemcke 1999a, 1998; A. Jelmert, pers. comm.), Undaria pinnatifida spores (Mountfort 1997), and zooplankton (A. Jelmert pers. comm.; Mountfort 1997). Field studies have included tests on the use of filtration (Parsons et al. 1997; T. Waite, pers. comm.), heat (e.g., Rigby et al. 1998; Prentice and Thornton 1997; Rigby and Hallegraeff 1994; D. Mountfort, pers. comm.), hydrocyclones plus UV irradiation (A. Jelmert and H. Nilsen, pers. comm.), and discharge to sewer (A. Cohen, pers. comm.), and are proposed for filtration plus UV irradiation (note: the author is involved in this proposal). However, it remains the case that research into the treatment of ballast water is in the early stages of development.

Several reviews have been published on technologies for ballast water treatment (e.g., NRC 1996; Carlton et al. 1995; Gutteridge, et al. 1993; Laughton et al. 1992) with recent reviews by Oemcke (1999a, b). This paper summarizes the findings of the latter review, with particular emphasis on the interactions between the nature of the shipping industry and the efficacy of disinfectants in particular circumstances. The requirement for an overall framework, within which to compare ballast water disinfectants, and some of the research needed for this system are discussed. Some of the disinfectant options reviewed in Oemcke (1999a, b) are shown in Table 1.

The treatment and management of ballast water can be conducted at a number of stages of a ship’s voyage (see Carlton 1985 or Hayes and Hewitt 1998). It can be conducted on shore or on ships, and before, during, or after trips on which ballast water is carried. Figure 1 shows a summary of the locations at which ballast water management and ballast water treatment can be conducted. This figure includes the options identified by Carlton et al. (1995), except non-discharge of ballast and extending voyage length. Management techniques can be used to control species transfer without the addition of water disinfection technologies. The treatment options would
Figure 1. Ballast water treatment options within the shipping and ports industries.
require the addition of physical or chemical disinfectants to ballast water.

The feasibility of the use of various management and treatment strategies and/or technologies for ballast water treatment is affected by a wide range of technical issues, including the following.

- **Cost to conduct** (on a comparable basis, for example US$/mt).
- **Time required for completion of treatment**. Some methods will not be able to be completed within the duration of a voyage, depending on the route.
- **Technical impediments**. A particular impediment to various treatments, as described below, is the ability to achieve adequate mixing.
- **Availability of proposed technologies at the required scale**.
- **Long-term toxicity**.
- **Efficacy of disinfectants**. For the ballast treatment options, a range of disinfectants could be efficacious, but the disinfectants vary with the stage of a voyage.

In order to move forward, it is necessary for the industry and regulators to be able to select ballast water treatments that work and are cost-effective. There are competing issues, where managers may tend to regulate conservatively and industry will want the lowest possible combination of cost and risk to meet regulations. This paper reviews the technical issues for treatment at the various stages of a ship's voyage, and proposes the development of a framework for comparing options that will assist in making these management decisions.

### Port-based Treatment Systems

*(Shore or Treatment Ship)*

Treatment on land is often favoured by regulators and managers, as the quality of treatment is often considered more controllable than with any other system. Treatment on land can be conducted at a shore-based plant or by a treatment ship (e.g., Carlton *et al.* 1995; Gutteridge *et al.* 1993). The technological requirements for effective treatment at port-based facilities can be met in many ways and would be site specific. Several different types of filters can be used to remove a large number of organisms (e.g., sand filters, pressure filters, screens, membranes), pH can easily be adjusted to give optimum conditions for disinfectants, and oxidant residuals can be removed.

The difficulties, real or perceived, of implementing port-based treatment appear to have limited consideration of this option, and it is likely that in many cases implementation will be very difficult. The use of potable water is very unlikely to be cost effective due to the high standards of treatment and high value of fresh water supplies (Oemcke 1999b).

Discharge to sewer is unlikely to be widely effective because not all sewage is disinfected, and much is only disinfected to the level required for the removal of bacteria; many ports are distant from sewage treatment plants large enough to take their flows; and there is anecdotal evidence that highly saline water (particularly saline shock loads) upsets nutrient removal and sludge settling in biological sewage treatment systems. It may have a role in areas where ballast discharges are predictably low and is being trialed in San Francisco (A. Cohen, pers. comm). One likely benefit from discharge to sewer is the removal of cysts in primary sedimentation processes.

Options for the shore-based treatment of ballast water, separate from potable water and sewerage systems, have been proposed. Gutteridge *et al.* (1993) presented concept designs for a shore based system and several authors have discussed various alternatives (e.g., Carlton *et al.* 1995). A system of cyclonic separation and UV-irradiation has been proposed for VLCCs (very large crude carriers) where ballast is purchased from a port-based supplier, or alternatively from a specially equipped tender (H. Nilsen and A.
(a) Reballasting with non-residual treated ballast

![Reballasting diagram]

(b) Ballast dilution (flushing) with treated ballast water (new or recirculated)

![Flush diagram]

Figure 2. Representation of the use of nonresidual disinfectants for in-transit treatment of ballast water, showing that, in general, they are no different from ballast exchange.

Jelmert, pers. comm.). VLCCs have very high costs for ballast exchange and well-defined trade routes, which makes a system of purchasing treated ballast water more likely to be attractive on financial grounds compared with other potential markets within the shipping industry.

IN-TRANSIT TREATMENT

In-transit treatment must be capable of achieving an effective disinfection residual throughout the vessel during transit. Options that produce no residual, such as filtration, cyclonic separation, high power ultrasound, magnetic treatment, and UV cannot be utilized for in-transit treatment, as the organisms must be moved to the treatment plant. The hydraulic inefficiencies of ballast tanks mean that all water will not pass through the treatment plant. Figure 2 helps to illustrate how the use of nonresidual in-transit treatment is no more effective than ballast exchange at sea. This can also be illustrated by assuming that a pumping system ensures that 90% of the ballast water in a ballast tank passes through a (nonresidual) in-transit treatment system, which then inactivates 99.99% of organisms. In this case, 10.01% of the organisms within the ballast tank survive treatment due to hydraulic inefficiency, even though the disinfection system inactivates 99.99% of the organisms that pass through it.

Ideally, in-transit treatments will be broadly biocidal and capable of being mixed into ballast water during ballasting. Treatments with an ability to obtain an evenly distributed residual include ozone, chlorine, chlorine dioxide, bromine, hydrogen peroxide, pH adjustment, heat, proprietary biocides, and copper sulphate, among others. For oxidizing biocides (e.g., ozone, chlorine, bromine, hydrogen peroxide, and chlorine dioxide), chemical reduction of the residuals at the sediment-water interface and areas of corrosion are likely to adversely affect the most cost-effective dosing methods (Oemcke and van Leeuwen 1998a, b). It may be possible to arrange chlorine dioxide dosing to make it effective, although benthic organisms in sediments will probably be difficult to remove and local areas of corrosion may have a negative effect.

A large body of data suggests that dinoflagellate cysts are very difficult to remove from ballast water with any biocide other than heat (e.g., Oemcke 1999a; Hallegraeff et al. 1997; Montani et al. 1995; Bolch and Hallegraeff 1993; Ichikawa et al. 1992). It is conceptually possible to pre-treat by filter or cyclone to remove these resistant organisms prior to applica-
tion of the biocide. Pre-treatment would need to be conducted during ballasting prior to in-transit application of biocide, a two-stage treatment process that increases treatment plant complexity and adds cost.

Currently, a promising option for in-transit treatment to remove cysts of dinoflagellate algae is heat. The ship’s engine cooling system and exhaust are areas where free waste heat can be obtained, giving this option the opportunity to be relatively cost neutral compared with ballast exchange at sea. However, potentially important pathogens (e.g., *Aeromonas salmonicida*, *Vibrio cholerae*) will not be affected, and a wide range of organisms remains to be tested. Waste heat will not be suitable for short voyages, due to the time required to transfer adequate heat into the water, and may not work in cooler waters due to heat loss to the environment (Rigby et al. 1998). No detailed examinations on the corrosion potential have been conducted. Although Rigby et al. (1998) believe this will not be a problem, it requires investigation before heat treatment is adopted. Heat may affect the stress loadings of the vessel by causing differential expansion of the ship superstructure (Carlton et al. 1995), which also requires attention. The use of additional waste heat from the exhaust may improve the process, and the use of recirculation, rather than the ballast dilution approach, may improve the efficacy of heat treatment (D. Mountfort, pers. comm.), although it is potentially more expensive, due to the heat exchangers.

**Shipboard Treatment during Ballasting**

Shipboard treatment during ballasting has important advantages over treatment during deballasting. Water can easily be taken in through the ballast pumps during ballasting, whereas during deballasting it is discharged through multiple outlets. It should be noted that 5–20% of the ballast on board is often deballasted during a ship’s approach to port, particularly from the topside tanks (Hayes and Hilliard 1996). Further, ballasting is often conducted at a slower rate than deballasting (e.g., Hayes and Hilliard 1996). This will reduce the size of shipboard treatment plants required during ballasting compared with treatment during deballasting, as treatment plant size is roughly proportional to flow rate.

Solids separation (e.g., screening or hydrocyclones) is the simplest system for ship-board treatment. It requires that the organisms removed by the screens can be returned to the source port, to avoid expensive treatment of the screenings. Screening can handle sediment loads if appropriate units are selected and designed appropriately. For treatment of larger organisms in ballast water, a 50-μm screen appears to be appropriate, and for the removal of dinoflagellate cysts, 20-μm micron screens will be necessary (Oemcke 1999a, b). Due to their high density, dinoflagellate cysts should be removed by hydrocyclones (Anderson et al. 1985), and new systems are claimed to be effective for removal of a range of organisms and particles to less than 10μm (H. Nilsen, pers. comm.).

Ultraviolet irradiation (UV) has considerable potential as a secondary ballast water treatment, following solids separation during ballasting (Oemcke 1999a, b; 1998). UV will require pre-clarification to be effective, both to reduce turbidity and remove UV-resistant dinoflagellate cysts (Oemcke 1999a). The example of a shipboard ballast water plant, for treatment during ballasting (Figure 3), shows how a UV plant might be configured for ballast water disinfection.

Ozone is unlikely to be an applicable treatment during ballasting, due to the high doses of or fine filtration required to remove resistant organisms (Oemcke and van Leeuwen 1998a). Chlorine is similarly constrained. However, a system that uses membrane filtration followed by chlorination is proposed for cruise ships (Carless 1998). This system has potential as cruise ships use small amounts of ballast water, so although the cost burden of high technology options is high, their simplicity is beneficial. Furthermore, membrane filtration alone will remove all organisms except for viruses. This approach suggests that some combinations may have potential for ships using
Table 2. Refined list of ballast water treatment alternatives for shipboard treatment adapted from Carlton et al. (1995) by Oemke (1999a, b)

<table>
<thead>
<tr>
<th>Treatment option</th>
<th>Zooplankton and fish</th>
<th>Effective against classes of organism</th>
<th>Attached bacteria</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Macroalgae spores</td>
<td>Dinoflagellate cysts</td>
</tr>
<tr>
<td>Organisms present in source port</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Ballast “micromanagement”(^a)</td>
<td>Partially effective, should be pursued as risk reduction strategy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2a. Filtration during ballasting (50 μm)(^b)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>2b. Filtration during ballasting (20 μm)(^b)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>2c. Filtration during ballasting(^b) 50 μm + cyclone</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>2d. Cyclonic separation alone(^b)</td>
<td>research</td>
<td>research</td>
<td>✓ probably</td>
</tr>
<tr>
<td>3. Enhanced mechanical damage at pump(^c)</td>
<td></td>
<td></td>
<td>requires research</td>
</tr>
<tr>
<td>4. Ultraviolet irradiation(^a)</td>
<td>✓</td>
<td>research</td>
<td>note 2</td>
</tr>
<tr>
<td>5. High power ultrasound(^d)</td>
<td>Maintain “watching brief” for a few years until technology develops</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6. Other new technologies(^a)</td>
<td>Maintain “watching brief” until technology develops</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7. Chlorine dioxide(^e)</td>
<td>Effectiveness unknown, requires research</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Organism survives ballast uptake

| 8. Heat treatment in-transit\(^c\) | ✓ | ✓ | ✓ | partial | ✓ |
| 9. Chlorine dioxide in-transit\(^e\) | Effectiveness unknown, requires research | | | | |
| 10a. Ballast dilution (3 volumes) | > 85-90% effective for pelagic, effect of dead spots must be researched | | | | |
| 10b. Reballasting | >90% effective for pelagic, implementation difficult for many ships | | | | |

Organism survives journey

| 10c. Backup exchange zones | Same as options 10a and 10b except for potential risk to backup zone | | | | |
| 10d. Part load then deballast (return to sea or backup zone) | 100% effective within port as no ballast is discharged, potential risk to backup zones | | 100% effective where viable | | |
| 11. Non-discharge of ballast water | | | | | |
| 12. In situ extermination | Difficult to achieve mixing or find suitable disinfectant | | | | |

\(^a\) Screening and/or cyclonic separation will be necessary as a pretreatment;\(^b\) 20-μm screens and cyclonic separation likely to be effective; 50 μm filtration or UV alone ineffective.\(^c\) Assumes adequate time and heat transfer are available

Small volumes of ballast (e.g., cruise ships), although they may not have potential for larger vessels.

High-power ultrasound is a new technology that may eventually be effective for ballast water treatment. The technology is still in the developmental stage, so very few good data are available on costs per unit of water treated in large installations, or on the effects of interfering substances or the limitations of the technology (e.g., suspended solids). The relationship between laboratory tests and full-scale plants cannot be determined until full scale plants are built and evaluated for disinfection applications. A “watching brief” is, therefore, the appropriate approach to this technology at present as it will probably take several years before developments reach the stage where testing for efficacy against ballast water organisms is appropriate.

Chlorine dioxide is an effective cysticide that may be appropriate for treatment during ballasting. The main concerns with chlorine dioxide are cost and the possible environmental toxicity of by-products.

**Biocidal Shock Dosing**

The use of biocides to treat ballast during a vessel’s approach to port, especially vessels that have been identified as a risk by a port state, is a conceptually attractive option, but has a variety of difficulties and concerns. These include identifying a chemical that works, identifying a chemical that is safe to han-
dle and not prohibitively expensive, identifying a chemical that is safe to discharge to the environment, and determining a method for thoroughly mixing the chemical into the ballast tanks.

Loaded vessels carrying no ballast on board (NOBOB) entering the Great Lakes of North America have the potential to be dosed with biocide to inactivate the organisms in nonpumpable ballast residuals remaining in empty ballast tanks. Lubomudrov et al. (1998) and Moll et al. (1998) recommend glutaraldehyde, which they believe will have time to break down before its eventual release to the environment, and could be dosed at a station by properly trained staff. It must be noted that these chemicals present a high level of risk to the health of staff handling them and may be too unsafe for the use of these chemicals. RNT (1997) recommend the use of glycolic acid or glutaraldehyde. This approach may be suitable for areas like the Great Lakes, where ships enter without ballast and then trade within the system, and can be dosed during river passages en route to the lakes; however, the literature suggests that high doses will be required.

**Ballast Management Options**

There are several management options in Figure 1 and Table 2, which, in addition to the treatment options, complete the picture of potential ballast water treatment technologies. Much of the current effort in treatment technologies is motivated by the inadequacies of these options in terms of both safety and efficacy for the removal of organisms. However, it may be possible to improve the efficacy of these practices, particularly ballast exchange, and they will have an important role in the control of introductions from ballast water. Further research is necessary (Oemcke 1999a, b).

**Model of Ballast Treatment Systems**

As discussed above, the treatment of ballast water on shore (or a treatment ship) will depend on local site constraints, land availability, infrastructure availability, and local discharge regulations; a very wide range of technologies is suitable. Designers and operators of treatment facilities should know the options that can be applied for treatment and be able to make decisions based on what is known about the efficacy of a very wide range of treatment technologies and alternatives for organism removal (discussed in more detail in Oemcke 1999a). However, shipboard treatment is a more highly constrained system that requires careful consideration of the alternatives.

Carlton et al. (1995) proposed a list of potential ballast water treatments, which is refined to the 12 currently strong options for shipboard treatment and shown in Table 2. Their five options for prevention of organism intake have been refined to a single option called “ballasting micromanagement” in Table 2, and the model for filtration is refined to two levels of screening (20-μm and 50-μm). Options from the list of Carlton et al. (1995) that have been omitted are those that recommend in-transit treatment with nonresidual biocides or biocides that need to be evenly and reliably distributed to be effective. The use of shore facilities to provide treated water, use of potable water, discharge to sewage, and options specific to sediments have been omitted from the list as they are not considered widely viable. Tank coatings and oxygen deprivation are not effective treatments.

**Comparing Ballast Treatment and Management Options**

Comparing ballast water treatment options is the most important issue confronting technologists involved in ballast water management. The previous sections have focused on a review of the options available for the treatment of ballast water. As indicated, a number of alternatives can be rejected on the grounds of technical feasibility, lack of broad applicability, or toxicity. Furthermore, it is clear that the financial issues vary across the industry. However, in general the ballast water treatment alternatives cannot be objectively compared, either between the potential locations for treatment or technologies.

Treatment options are typically compared on the basis of cost to reach an agreed standard, within any other existing constraints. At present two de facto standards are being used for ballast water treatment, but they are not recognized as being standards. I consider these to be standards only because they are the only widely used basis for comparing disinfectants and management schemes.

The first de facto standard is based on the efficiency of ballast exchange processes (ballast dilution or flushing and rebalasting), which is somewhere around 90%, and often much lower. An efficiency of 85% has been treated as acceptable by the U.S. Coast Guard (Reeves 1997). Hallegraeff (AQIS 1998) suggests that ballast dilution is about 85 to 95% effective. The second de facto standard is that implied by
the current approach to ballast disinfection, where 100% control of the resting cysts of certain species of dinoflagellate algae is the target of treatment. These two de facto standards are incompatible with each other, and mean that quantitatively comparing the treatment processes and management options is impossible. This is because

- the exchange efficacy standard is biased towards the selection of ballast exchange as an option, having grown out of the use of that option; and
- there is no basis for requiring any treatment to remove or inactivate all algal cysts, as no treatment other than heat is available.

Criteria for the treatment of ballast water are required to determine if the processes are achieving an appropriate level of removal. To do this, it is suggested that the following criteria be fulfilled:

1. Develop an understanding of the organisms that are desirable to remove from ballast tanks, which is the subject of considerable research. This does need to be a complete understanding, but can grow with the scientific contribution.

2. Select indicator organisms. For example, *Vibrio cholerae*, resistant motile/pelagic unicellular marine alga or protozoa, sexual stages of *Undaria pinnatifida*, *Gymnodinium catenatum* hypnecysts, *Dreissena polymorpha* pelagic veligers, and *Asterias amurensis* larvae may be considered appropriate at present.

3. Determine a desired level of removal, based on the available risk assessment tools.

With a set of indicator organisms and a desired level of removal, ballast water treatment and management options can be selected on the basis of their ability to remove these organisms to the required level. The treatment and management options can then compared on an objective basis such as cost, environmental hazard, time required, space required, etc., for treatment to the mandated level.

A preliminary dataset can be used to establish treatment requirements in the short term, with scientific advances used to refine the criteria used for selecting between options. Without this system, it will be difficult to resolve the competing claims of proposed solutions, research will remain relatively unfocused, and managers will be constrained by a lack of performance requirements in setting objectives. The establishing of standards will begin a debate on standards that can be resolved in the long term by research. The process for setting standards in the water supply industry is similar. Great gains were made by the removal of basic faecal contamination, with an international process of refining standards and targets an ongoing feature of the water supply industries research effort.

For the ballast water treatment industry several current fields of research will help to refine the system of standards over time. These include the following:

- Efforts to understand the dynamics of the survival of organisms present in ballast tanks (e.g., Hall et al. 1998; Ruiz and Hines 1998; Taylor-Wood et al. 1997).
- Efforts to understand or estimate the inoculum of an organism that is necessary to infect a new site (e.g., Ruiz and Hines 1998).
- Improved understanding of risks; for example, quantitative probabilistic approaches (Hayes 1998; Hayes and Hewitt 1998); semi-quantitative approaches (Hilliard and Raaymakers 1997; Hayes and Hilliard 1996); and quantitative approaches (Carlton et al. 1995). The qualitative probabilistic approaches will be the most precise risk assessment, but probably require enormous investment.

**The Required Level of Assessment**

Comparisons should be conducted on the basis of individual ships and their trading patterns, on the required level of organism removal for that trading pattern, and over the life of the ship. Costs of ballast water treatment and management techniques cannot be generalized for the whole shipping industry due to variation in ship design, ballast pumping rates, ship purpose, and trading routes. Treatment and management options should also be compared over a lifetime, not over a single trip, to reduce distortion of cost comparisons.

Depending on the management or treatment technology, the cost of ballast management is related to either the total ballast capacity and trip length or to the size of ballast pumps, each of which vary significantly. Ballast water treatment methods will vary in their efficacy depending on the conditions to which they are subjected. For example, lower doses are effective for UV irradiation of algae as trip length increases and higher temperatures are possible for longer trips when heat treatment is used. Some organisms will be inactivated without treatment, depending on temperature changes during trips or length of trip.
It will be valuable to understand whether the concentration of organisms in ballast water is important, or if the number of organisms discharged is more important, in order to establish a sensible set of treatment criteria. If it is purely the number of organisms, then treatment systems for different vessels will necessarily differ. A 90% effective treatment (e.g., exchange) for a ship discharging 1,000 mt of ballast water will release the same volume of untreated water as a 99.9% effective treatment (e.g., filtration + UV irradiation) on a ship discharging 100,000 mt of ballast water.

Moving Forward

The development of effective ballast water treatment and management techniques requires the development of a set of logical treatment standards. Without such standards, the options for treatment and management cannot be compared objectively and the debate about solutions to ballast water will remain unfocused, as it is presently.

Science can be further developed following the setting of standards. This will most likely include some of the following:

- A step forward in the debate about risk assessment methodologies, as management questions increasingly become the focus of risk assessment. For example, questions about the level of risk assessment required will be coupled with an assessment of the ability to respond adequately. This is likely to result in a shift in resources towards developing solutions rather than quantifying risks to a very precise level.
- The interrelationship between infectious dose and treatment will be explored in detail, as the costs of meeting tight standards will begin to become apparent.
- Understanding the issue of concentration and dose will become important, as it will have an impact on the cost of treatment across the industry.

Specific Technological Recommendations

To progress forward on the development of technologies listed in Table 2, the following specific recommendations are put forward, in no particular order.

Ballast Treatment

1. Screening/cyclone pilot tests. Pilot testing should be conducted for screening at 20µm–50µm, to determine its ability to handle sediment loads and blooms of plankton and phytoplankton. This pilot testing will find the operating constraints so that systems can be appropriately designed and enable full-scale cost data to be accurately determined.

2. UV laboratory tests. Further laboratory testing on UV disinfection is required. This testing should target species of phytoplankton and protozoans that will pass clarifiers and for which disinfection efficacy data are not currently available. It must account for dark repair and the effect of storage on inhibiting photorepair mechanisms.

3. UV pilot tests. Pilot testing for UV+screening/cyclone systems should be pursued in addition to further laboratory testing. There are enough data demonstrating that UV has considerable potential for ballast water treatment during ballasting, and full-scale design data need to be gathered. The pilot testing must aim to test the limits of the UV system.

4. Ultrasound. High-power ultrasound should be viewed cautiously by ballast researchers until the costs and operating constraints of full-scale systems are understood. This technology should be watched, as it may have potential for treatment during ballasting.

5. Heat treatment testing. In-transit heat treatment needs to be researched to determine where this will be an appropriate solution. Modelling of flow processes may enable systems to be designed that improve the transfer of heat into the ballast tank, and can be designed into new vessels.

6. Chlorine dioxide laboratory tests. Laboratory-scale tests of chlorine dioxide should be considered for addition to any tests being conducted on cysts, to determine if it is effective for their treatment. It is a highly effective cysticide, and may have potential for ballast treatment, either shipboard or land-based.

Ballast Management

1. Ballast exchange dye tracer tests. Testing of the effectiveness of ballast dilution and reballassing at sea should be further pursued. Tracer studies have had problems with evenly distributing dye into the water, and it would be preferable to use a method that injects a pulse of dye into the incoming ballast water during the exchange process. Data from well-conducted tests may be
useful to help design more effective systems or to eliminate this option from consideration.

2. Modelling the effectiveness of ballast exchange. Modelling of a ballast tank using a flow-analysis package and including the internal structures of the tank is necessary to evaluate the effectiveness of dilution and to design good dilution systems for new vessels, if this option is appropriate.

Acknowledgments

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UV Disinfection of Ballast Waters: Effects of Organism Size on System Scaling

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ABSTRACT: Ballast water has been demonstrated to be one of the principal vectors for unintentional introduction of non-native species. Although a number of treatment options, both physical and chemical, have been proposed, UV sterilization remains an especially viable and environmentally benign approach. Developments in UV technology using high-powered excimer sources in the germicidal region of the UV spectrum (developed to treat bacteria in metal-working fluids) have enabled the efficient delivery of doses capable of inducing acute and latent phototoxicity in a wide variety of organisms. In this investigation, we evaluate the efficacy of high-intensity UV irradiation at applied doses of 10-100 mWsec/cm² in controlling planktonic organisms likely to be entrained in ballast water. These include larval and adult crustaceans, larval bivalve mollusks, larval fish and microalgae. Since this technology will likely be combined with some physical filtration for shipboard installations, the relationship between organism size and effective UV dose becomes an important consideration. We present preliminary data for a representative range of organisms using an experimental flow cell.

Key words: ultraviolet light, filtration, system scaling

INTRODUCTION

The introduction of non-native aquatic species into the North American waterways has been occurring for as long as transoceanic travel has existed. In fact, representatives from virtually every group of aquatic organisms have been introduced somewhere in the world (Morton 1997). The scale of exotic species introduction is enormous: 136 nonindigenous species are known from the Great Lakes and at least 43 of these have arrived since 1960 (Mills et al. 1993). Of the 150 nonindigenous species that have been discovered in San Francisco Bay, at least 21 of these have colonized the Bay since 1973 (Carlton et al. 1990). In Coos Bay, Oregon, exotic species number approximately 80, and in Chesapeake Bay approximately 15.

How to curtail the invasion of non-native species from North American rivers and lakes is a critical question. It has repeatedly been shown that ballast water is the principle vector for unintentional introduction of these nonindigenous organisms into U.S. waters (Wiley 1997; Reeves 1997; Carlton and Geller 1993), and likely facilitated the introduction of zebra mussels (Dreissena polymorpha), to North America. Support for this argument was given by Carlton and Geller (1993) in a study where ballast water from 159 cargo ships that had traveled from Japan to Oregon were sampled, discovering 367 distinct taxa representing 19 phyla. This illustrates that ballast water is a medium in which a diverse community of organisms can survive and even thrive during transport over many miles.

There are some controls that can minimize the chance of successful colonization by an exotic aquatic species. A currently favored technique is the
exchange of ballast water at sea. The objectives of this technique are to flush out organisms and bring the salt concentration of the ballast water to approximately 30 ppt (Reeves 1997; Wiley 1997), limiting the survival of salt-intolerant organisms. However, potential complications of ballast exchange still exist. Because of the amount of ballast that would have to be removed at one time, it may be unsafe for the larger ships to exchange enough water. Ballast exchange may also be waived in poor weather, it may be ineffectively performed, or there may still be significant survival of exotic species protected in sediments remaining in the tank even when the exchange is performed within the bounds of existing legislation (Reeves 1997; Wiley 1997). The direct treatment of ballast water may be a more desirable option.

In 1990, the U.S. Congress enacted P.L. 101-646, the Non-Indigenous Aquatic Nuisance Prevention and Control Act. In 1992, the Marine Board of the National Research Council began the “Assessment of Ship Operations [Ballast] Technologies for Controlling the Introductions of Non-Indigenous Organisms”. The International Maritime Organization has created a Ballast Water Working Group with a mandate to develop international guidelines governing both ballast water exchange and the development of methods for treatment of ballast water. Treatment options include both shipboard and shore-based operations and a variety of potential treatments are currently under consideration. The principal categories of treatment under particular scrutiny are acoustics, biocides, deoxygenation, electric pulse/pulse plasma, filtration, magnetic, thermal, and ultraviolet light. Although many of these techniques are currently in use in water treatment, several are impracticable for shipboard operation. For example, the mechanical and energy requirements for heat sterilization of ballast water are substantial. Initial attempts to demonstrate solutions have, therefore, focused on what is both feasible and practical. A recent study by Battelle (1998) concluded that “UV treatment is currently the best suited for secondary treatment of ballast water.”

**Rationale for UltraViolet (UV) Radiation**

The ability of ultraviolet (UV) radiation to inactivate water-borne microorganisms has made it an excellent choice as a disinfectant in the drinking water and wastewater treatment fields. Despite the fact that the potential for water treatment with UV radiation has been known since the beginning of the century, UV light as a practical means of treating ballast water has only recently received attention (Wright et al. 1997). The most important advantage UV has over other disinfectants is its ability to treat pathogenic organisms without the addition of chemicals that may produce toxic byproducts. In this way, treatment can be environmentally friendly and still remain cost effective.

One aspect of the toxicity of UV radiation involves photochemical damage to DNA within the cells of microorganisms. Nucleic acids in living cells absorb light in the UV wavelengths (240–300 nm), inducing dimerization of the thymine bases due to a C5, C6 double bond breakage. This distorts the sugar-phosphate DNA backbone rendering the cell incapable of replicating (Liu et al. 1995; Water Environment Research Foundation 1995; Russo and Russo 1993; Skeldon 1991). This process dominates for smaller organisms and can be modeled as a photochemical reaction between light and the DNA molecule.

UV radiation has been proven effective against vegetative and spore forms of bacteria (0.2–5.0 mm), viruses and bacteriophages (0.02–0.2 mm), and many other pathogenic microorganisms (Sobotka 1993). Some of these include *E. Coli* (Mechser et al. 1991) *Legionella sp.* (Yamamoto et al. 1987; Liu et al. 1995) *Bacillus subtilis* (Sommer and Cabaj 1993) hepatitis A virus (Battigelli et al. 1993; Wiedenmann et al. 1993), Coxackie virus B-5 (Battigelli et al. 1993), rotavirus strain SA-11 (Battigelli et al. 1993), and the F-specific RNA bacteriophages, MS2 and jX174 (Battigelli et al. 1993; Wiedenmann et al. 1993; Havelaar et al. 1991).

Since many microorganisms have the ability to reactivate or repair the DNA lesions caused by UV light over time (Russo and Russo 1993; Mechser et al. 1991; Yamamoto et al. 1987) and there is no residual toxin in the system, the standard UV treatment system used on waste or drinking water produces a sufficient dose to cause the immediate death of the pathogen. Objectives for ballast water are similar but distinct. The larger organisms may require higher doses for sufficient photochemical effects to accumulate to produce an outright kill. For these organisms, photobiological effects, such as disruption of germinal organs, damage to eyes, or other effects, may provide a more efficient path to the objective of a ballast
### Table 1. Relative sizes of microorganisms found in water

<table>
<thead>
<tr>
<th>Microorganism</th>
<th>Approximate Size</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Viruses</td>
<td>.02 – 1 mm</td>
<td>Hepatitis virus, 0.02 mm; HIV, 0.08 mm</td>
</tr>
<tr>
<td>Bacteria, cocci (spherical) and bacilli (rod-shaped)</td>
<td>0.25 – 5 mm</td>
<td><em>Pseudomonas</em>, 0.5 – 0.62 mm; <em>Vibrio cholerae</em>, 1 – 10 mm</td>
</tr>
<tr>
<td>Protozoans</td>
<td>1 – 80 mm</td>
<td><em>Myxospora</em>, 5 – 30 mm; <em>Microsporidians</em>, 1 – 10 mm</td>
</tr>
<tr>
<td>Fungi</td>
<td>1 – 100 mm</td>
<td><em>Aphanomyces</em></td>
</tr>
<tr>
<td>Cyanobacteria (blue-green algae)</td>
<td>0.2 – 2 mm</td>
<td><em>Microcystis elefants</em>, 2-6 mm; <em>Spirulina subsalsa</em>, 0.4-4 mm; <em>Chroococcus limneticus</em>, 6-12 mm</td>
</tr>
<tr>
<td>Phytoplankton (includes diatoms, dinoflagellates, cryptomonads, macrophyte spores, and other pico-, nano-, micro-, and colonial phytoplankton)</td>
<td>2 mm – 2 mm</td>
<td><em>Skelatoma</em>, 7-15 mm; <em>Thalassiosira eccentrica</em>, 40-120 mm; <em>Cryptomonas, pseudobaltica</em>, 18-30 mm; <em>Chroococcus amphioxera</em>, 10-19 mm; <em>Euglena proxima</em>, 18-25 mm; <em>Pfiesteria</em>, 5-450 mm (cyst stage, 7-60 mm); <em>Gymnodinium</em> (red tide species), 20-25 mm; <em>Gonyaulax</em> (red tide species), 28-43 mm</td>
</tr>
<tr>
<td>Zooplankton</td>
<td>30+ mm</td>
<td><em>Zebra mussel veligers</em>, 30 – 65 mm; <em>Adult calanoid copepods</em>, 1.6 – 12 mm; <em>Various crab and shrimp zoa</em>, 5 mm; <em>Starfish</em> (<em>Asterias rubens</em>) larvae, 2 mm</td>
</tr>
<tr>
<td>Fish eggs</td>
<td>0.5 – 5.0 mm</td>
<td></td>
</tr>
<tr>
<td>Larval fish</td>
<td>2+ mm</td>
<td></td>
</tr>
</tbody>
</table>

A water control system—preventing the nonindigenous species from colonizing its new ecosystem.

The optimal light source for a ballast water control system is likely to be very different from the optimal system for drinking water treatment. In addition to larger target organisms, the presence of suspended particles, such as dirt and algae, will reduce the range of UV in water. Microorganisms may be shielded by these particles and, thus, not be affected by the radiation (Skeldon 1991; Taylor 1988). These obstacles could be prevented through a physical pre-treatment process, such as filtration (Liu et al. 1995; Skeldon 1991; Taylor 1988).

In the Great Lakes Ballast Technology Demonstration Project supported by the Northeast-Midwest Institute and the Lake Carriers Association, initial emphasis has been placed on a physical filtration system. In this regard, a major practical consideration is the smallest particle size capable of being filtered at the very large flow rates involved with ballast water loading. Such a system can be regarded as a pre-treatment. Secondary treatment (like UV) must be capable of effectively dealing with particles too small for physical filtration and should include bacteria. The discovery of cholera in shellfish and fish in Mobile Bay, Alabama (McCarthy and Khodamaty 1994) was traced to ballast water in vessels that had recently visited South American ports. In advance of practical demonstration, it was generally felt that the lowest cut-off size for effective physical filtration is 100-200 mm. Recent results (see reports from Parsons and Cangelosi in these proceedings) suggest this value is between 25 and 50 micrometers. These encouraging results still require an effective secondary treatment since many pathogens are considerably smaller (see Table 1). *Vibrio cholerae*, for example, is typically 1-10 mm.

Preliminary experiments using a medium-pressure mercury lamp and notch filters indicated that monochromatic UV light was toxic to late-stage dresedien larva. Pre-settlement larvae exposed to 254- and 280-nm light at 100 mWsec/cm² completed settlement, but subsequently all died. Control larvae had 100% survival (Wright et al. 1997). Recent developments
in light sources suggest that a system tuned to a narrow spectral bandwidth optimized for ballast water is feasible. An excimer UV lamp currently manufactured by TII has been demonstrated to affect a three log removal of bacteria from industrial cooling fluids having the opacity of milk (Bissing et al. 1998).

**Experimental Methods and Results**

For the work described here, we have configured our experimental scale UV reactor to test the efficacy of excimer UV on aquatic organisms. In this system, test organisms are pumped through quartz tubing to triplicated exposure ports in the lamp housing. A fourth loop with no UV access serves as a control. Another test rig delivers 150 gallons per minute, either as a once-through pass or as part of a closed loop system. The once-through operation would simulate (at small scale) a ballast water loading operation, and the closed-loop would simulate a continuous treatment system that might be employed on board a vessel under way. Dose is a function of lamp output and exposure time (and is adjusted through flow rate). For the initial experiments presented here, the small-volume test stand was used in a once-through configuration.

The work reported here is a selection of data from a pilot project exploring the effectiveness of excimer UV light on a variety of planktonic organisms representative of those that might be entrained in an industrial intake or ballast water in an estuarine environment, such as the Chesapeake Bay. Some species that are not indigenous to the Chesapeake Bay have also been included, either because of ease of culture or because of their status as a nuisance species spread via ballast water.

Latent phototoxicity can be quantified only in terms of the biological effect achieved as a function of UV dose, the product of UV flux (mWatt/cm²) and exposure time (sec), when organisms are held in culture over several days or through different developmental stages. The quantification of latent effects places a substantial burden on experimental controls. Tests were performed on a range of organisms including, but not limited to, zebra mussels (*Dreissena polymorpha*), grass shrimp (*Palaemonetes pugio*), copepods (*Eurytemora affinis*), *Artemia salina*, Sheephead minnow larvae (*Cyprinodon variegatus*), and algae (*Chlorella vulgaris*). Representative data are shown in Figures 1-4.

**COPEPODS**

Copepods were maintained in culture at the Chesapeake Biological Laboratory using ambient Patuxent River water adjusted to a salinity of 12 ppt. Cultures were fed regularly with *Isochrysis galbana* at densities of >10⁵ cells/ml. Cultures were concentrated to exposure densities using 32-mm mesh Nitex sieves, sufficiently small to filter out all larval stages. Where needed, adults were filtered from the remaining culture using a 212-mm mesh sieve. Following irradiation, copepod suspensions were concentrated using 32-mm mesh sieves to 1/20th of their volume and larval counts made of each of three aliquots from each test replicate. Organisms were scored live or dead according to their response to physical stimulus, and numbers of live animals were compared with controls (see Figure 1).

Three different life stages were exposed to UV irradiation: stage 1-3 naupliar larvae (<60 mm), stage 1-3 copepodites (150-250 mm), and adult copepods (>500 mm). It can be seen that as the applied dose was increased, a stronger effect was measured. Similarly, higher doses produced a more acute effect. Differences in numbers of naupliar larvae between the controls and UV exposed samples represent the sum of naupliar mortality and reproductive delay or failure. That is, no new larvae hatched in the UV-exposed samples, suggesting an interruption of reproduction even at low doses.

**Artemia salina**

*Artemia salina* were commercially obtained cysts and were maintained in a dry condition until used. A
maximum of 5gm of *Artemia* was used in about 3 L of water. Water temperature was maintained between 25 and 30°C, and salinity between 5 and 15 ppt throughout the hatching period or for at least twenty-four hours. Light was maintained at about 2000 lux with constant aeration (without creation of foam) throughout the hatching period. The optimum pH for the hatching medium is between 7.5 and 8.5. After 24 hr, aeration was turned off and settling allowed for 5-10 min, because the empty shells will then float. Since *Artemia* nauplii are phototactic, one corner of the bottom of the incubating tank was illuminated to simplify separation of unhatched cysts and collection of nauplii. With an oven beaker or a siphon, concentrated *Artemia* nauplii were siphoned out into the *Artemia* net bag or into a 37-um-mesh sieve, for proper separation. The nauplii in the bag were rinsed in a gentle stream of water. Figure 2 shows increased killing at higher UV doses. Latent effects are difficult to determine due to changes in the control samples.

**FISH LARVAE**

Sheepshead minnow larvae (*Cyprinodon variegatus*) were collected from local estuarine sites. The minnows usually reach sexual maturity 3-5 mo after hatching, with standard lengths of about 27 mm for females and 34 mm for males. They were held at temperatures of 25-30°C, 20-30 indiv. in each rearing tank and fed Tetramin daily. When adults reached sexual maturity, they were kept in a temperature controlled system at 18-20°C. To initiate spawning, 75-80% of the water was changed and the temperature raised to 25°C with a photoperiod of 14-hr light and 10-hr dark. Adult females generally lay 10-30 eggs per spawn. To obtain embryos for a test, adult fish, generally five females and three males, were transferred to a 15-gal aquarium with the appropriate photoperiod, temperature, and salinity, 7-8 da before larval fish were needed. The spawning tank was fitted with spawning mats where the eggs were laid and adhered. Spawning usually began within 24 hr. Embryos spawned over a 24-hr period may hatch over a 72-hr period, so it is advisable to obtain eggs over several days to ensure that a sufficient number of newly-hatched (<24 hr) larvae will be available to initiate a test. When the mats contained a sufficient number of eggs, they were removed from the tank, rinsed in high-saline water with methylene blue (to prevent fungal infections), and incubated for 6-7 da at 25°C with gentle aeration. Water was changed daily. Approximately 24 hr before hatching, the salinity of the seawater was changed to that of the test salinity. Water chemistry was monitored over the hatching period. Larvae were fed newly hatched *Artemia* daily. The size of the minnows irradiated ranged from 0.4 to 0.9 cm. Higher doses were required for killing larger organisms than was needed for smaller organisms. Yet, even for these large organisms, a strong latent effect was observed for moderate doses (Figure 3).

**ALGAE**

The estuarine alga *Chlorella vulgaris* was cultured at the Chesapeake Biological Laboratory culture facility from in-house stocks. These were grown up as a 1L culture in sterilized filtered (16 ppt) water fortified with f/2 nutrient media. The culture was diluted to
5L with filtered estuarine water (16-ppt salinity) prior to the experiments. The approximate starting cell density was 2 \times 10^6 cells per ml. Following the exposure treatments, each 600-ml glass beaker containing 40C ml Chlorella culture was allowed to grow under continuous fluorescent light. At daily intervals, samples were taken for cell counting and microscopical examination, extraction of chlorophyll pigments with acetone, and direct in vivo chlorophyll fluorescence determination. The results of all three monitoring methods were consistent. The direct cell counts show significant inhibition of growth at doses of 70 mW/sec/cm² and 110 mW/sec/cm² relative to the control. The 70 mW/sec/cm² treatment, however, showed signs of recovery after 48 and 72 hr (Figure 4). The total extractable chlorophyll reflected this inhibition only at the highest dose, indicating that the chloroplasts at the 70 mW/sec/cm² treatment level remained viable. The simplest method, in vivo fluorescence measurements, corresponded well with total extractable chlorophyll and provides a facile approach to monitoring the effects of UV light on phytoplankton chlorophyll production. This technique may be used in future studies as a biological actinometer of UV flux or could be developed into a rapid evaluation technique analogous to the measurement of total coliforms used to benchmark drinking water disinfection.

**SUMMARY**

We have initiated an investigation on the latent and acute phototoxicity of UV radiation on organisms typically found in ballast waters. The current data suggest that organism size and morphology can affect the required UV doses. The doses required to kill larger crustaceans and fish may be an indication of photoprotection provided by carapace pigments and the greater mass of integument in larger organisms. There are also qualitative data suggesting that biological response is affected by the intensity, wavelength, and integrated dose of UV. The monochromatic output of excimer lamps can be tuned to optimize the efficiency of these processes. Latent phototoxicity (at 96 hr post irradiation) has been demonstrated at two-orders-of-magnitude lower doses than is required for immediate mortality.

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**LITERATURE CITED**


