Progress in the Management and Treatment of Ship's Ballast Water to Minimize the Risks of Translocating Harmful Nonindigenous Aquatic Organisms

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Abstract: Billions of organisms are transported around the world in some 10 billion mt of ballast water that are carried annually on ships. An increasing number of these organisms are becoming established in new locations, resulting in significant ecological damage worldwide as well as posing a threat to human health. A range of ballast water management guidelines and regulatory practices have been introduced by various countries in an attempt to minimize the risks of establishment from these inoculations. The International Maritime Organization is developing a set of international regulations, the use of which is likely to enter into force early in the new century. A range of potential ballast water treatment options have been suggested to kill biota or minimize the threat of water discharges; however, it is unlikely that a single treatment process will be developed that will eliminate all unwanted organisms in ballast water. Rather, a range of options appropriate for each particular ship and voyage, aimed at minimizing the risk, will emerge. Ocean exchange is currently the primary option that is being used. While this process can be effective in many cases, there are limitations which are likely to restrict its universal use. Ballast water heating utilizing waste engine heat has been demonstrated to be effective for killing many organisms and shows considerable promise for the future. A shipboard demonstration of filtration and testing of a hydrocyclone/ultraviolet irradiation system are in progress and will provide data to assess the feasibility of these options. A range of other biocidal and chemical processes have been or are being tested; however, the majority of these have been rejected at this stage on cost, effectiveness, practicality, or environmental grounds. Research and demonstration aimed at assessing these and other options are continuing.

Key words: ballast water, harmful aquatic organism, treatment, exchange, water heating

Introduction

Countless billions of marine organisms are transported around the world in the 10 billion mt of ballast water carried annually on ships to maintain their safety and stability at sea. Quantities and number of discharges continue to increase in major ports around the world with the use of larger ships, shorter transit times, and increases in world trade. The likelihood of these organisms surviving the voyage and becoming established in a particular port depends on many factors, including the types and nature of organisms, length of voyage, and environmental conditions at the ballasting and deballasting ports.

The consequences of nonindigenous organisms becoming established in a particular area can be quite devastating and have resulted in significant ecological and environmental damage worldwide as well as posing a threat to human health. The possible link between ballast water and dispersal of marine organisms was first suggested by Ostenfeld (1908) and Peters (1933). However, interest in ballast water discharges as a global environmental cause for concern has gained considerable impetus over the last decade with the documented establishment of a number of nonindigenous harmful aquatic organisms around the world.

Perhaps the most publicized of these is the zebra mussel (Dreissena polymorpha) in North America. First discovered in Lake St Clair in 1988 (Griffiths et al. 1991; Johnson and Padilla 1996), it has now become established in more than 50% of the waterways in the United States and is estimated to cost...
some US$500 million annually in nuisance costs resulting from blocking of power plant water intakes and water treatment, as well as fouling of fishing nets, boat hulls and buoys (Weathers and Reeves 1996). The toxic dinoflagellate, *Gymnodinium catenatum*, strongly linked to ballast water discharges, became established in the Derwent and Huon estuaries of Tasmania, Australia in 1972 coincident with the establishment of a new woodchip mill. This species has been responsible for the regular closure of shellfish beds to harvesting as a result of high Paralytic Shellfish Poisoning (PSP) toxin levels (Hallegraeff and Bolch 1992; McMinn et al. 1997).

Ballast water has been suggested as the vector for the introduction of the American Atlantic comb jelly, *Mnemiopsis leidyi*, in the Black Sea in the 1980s (Vinogradov et al. 1989). Since 1990, it has been responsible for a huge decline in commercial fisheries in the Black Sea where it has affected anchovy, sprat, and horse mackerel fisheries and also in the Sea of Azov, where anchovy and Azov kilka catches have been severely reduced (Vinogradov et al. 1996). It has now spread to the eastern Mediterranean Sea (Kidess and Neirnann 1994). Recent studies have suggested that choleran introduced in ballast water could present a health risk in some areas (McCarthy and Khambaty 1994). In particular, the survival of choleran by association with algal blooms and colonization of the chitinaceous exoskeletons of some marine organisms suggests that the role of ballast water in this case may be associated with the transport of intermediate hosts in addition to free choleran cells (Epstein 1993; Colwell and Spira 1992).

Carlton et al. (1995) have estimated that more than 3000 species are transported around the world by ship each day, and some 40 recent invasions have been mediated by ballast water (Carlton and Geller 1993). It is important to note that although significant emphasis has been placed on ballast water in relation to the translocation and establishment of unwanted aquatic organisms, other vectors such as hull fouling on ships and pleasure craft as well as organisms carried in oysters and fish for the aquarium trade may play a significant role.

As a result of these biological invasions, a range of ballast water management guidelines and regulatory practices have been introduced by various countries in an attempt to minimize the risks of new species becoming established. At the international level, the International Maritime Organisation (IMO) through its Maritime Environmental Protection Committee (MEPC) has been developing draft regulations with a target date for the adoption of a mandatory international instrument for ballast water management early in the new century.

These guidelines include a number of recommended management and treatment procedures that need to be considered by the ship’s Master in order to comply with the requirements prior to discharging ballast. Not all of these options are suitable or appropriate for use on all ships, and some are still being tested and developed. Research and development programs have been established in Australia, New Zealand, the United States, Germany, Canada, Japan, Israel, Ireland, Wales, Sweden, and Norway to investigate introductions and to support these regulatory efforts by testing the efficacy of various options and to identify and test appropriate alternatives.

This paper reviews the suite of management and treatment options that have been considered or are being utilized or developed for potential implementation both locally and at the international level.

**Management, Treatment and Target Species—Some Considerations**

A single practical, safe, environmentally acceptable, and cost-effective solution that will kill all living organisms, or those that could potentially germinate from material present in all ballast water contained in the wide range of ship’s tanks, is unlikely to ever become a reality. Rather, an overall strategy based on a range of management and treatment options to minimize the likely risks of organisms becoming established (once discharged) is currently and is likely to remain the generally accepted approach. This is certainly the approach that is being developed in Australia and several other countries as well as forming the current basis for the IMO regulations.

Another aspect relates to the types of organisms at which the control measures are aimed. Without some identification of particular species of concern, it is difficult to assess the likely efficacy of any ballast treatment option. The Australian approach has focused on a number of target species. The initial list of target species was developed to include a number of “model organisms” that were thought to have been introduced via ballast water into specific locations with significant environmental, aquaculture, or human health consequences, and had the potential
to become established in other ports if some control measures were not taken.

One particular model organism selected for the early research work was the toxic dinoflagellate, *G. catenatum*, which has resulted in the establishment of a costly toxin monitoring program in Tasmania to protect human health and to identify closure periods for harvesting of affected shellfish. *G. catenatum* produces resting cysts that can survive in sediments for many years and become established when appropriate conditions exist. Hence, it was considered that a study of its behavior under ballast tank conditions and various ways of killing both the motile and cyst forms of this organism would also provide a reasonable basis for assessing likely effectiveness of various treatment options on a number of other organisms.

Some researchers and countries do not consider that a targeted organisms approach is appropriate, since one ship alone can discharge many hundreds of different species that have the potential to cause problems if they become established. No doubt this debate will continue, but without some basis for testing and comparing the effectiveness of various treatment options, or for assessing compliance, it will be difficult to progress beyond accepting treatments that offer complete sterilization. Target lists can be changed from time to time to take into account changing conditions or observed introductions from other locations. It is interesting to note that *de facto* target species are sometimes used as a basis to handle a specific problem, even though the overall approach to management is regarded as non-target oriented. Examples include the use of salinity increases by flushing with ocean water in North America to minimize the risk of new *D. polymorpha* introductions and the banning of ballast discharges in New Zealand ports for ships arriving from specified Australian ports (namely Port Phillip Bay in Victoria and Tasmanian ports) because of concerns over possible introductions of *Asterias amurensis*.

In general, the risk-based approach seeks to assess the potential risk of one or more organisms becoming established within a port as a result of the water discharged. If the risk is below an identified level, the ship would not be required to undertake any treatment. For example, in a port where *A. amurensis* did not exist and its establishment would create major problems, there would be little risk involved for a ship discharging ballast water from ballast taken on in a port where this organism is known to be definitely absent. This is a very simplified case since, for example, the ship could contain residual sediments from a previous port where the organism is prolific.

There are several types of risks that need to be considered in assessing the overall risk of a particular organism becoming established. In addition to the biological risk (which is based on a multitude of factors related to organism presence, uptake, survival, discharge, establishment and impact), other risks such as social and management need to be taken into account. In Australia, a Decision Support System (DSS) based on a combination of all of these risks is at present being developed and will be used by the Australian Quarantine and Inspection Service (AQIS) in managing and implementing their ongoing ballast water program (Hayes and Hewitt 1998). This basic approach, albeit in a very basic form, has been used by AQIS for several years in implementing and managing its voluntary guidelines.

Initially the DSS will be implemented at a low level of sophistication since only limited information on input data such as biological presence and survivability will be available. However, the models being developed allow for the level of accuracy to be improved as further research and monitoring results become available.

**Management Options**

For any form of voluntary or mandatory ballast water controls to be acceptable, it is essential that these controls involve management and treatment options that are

- safe
- technically effective in killing the organism(s) of concern,
- cost effective
- environmentally acceptable, and
- practical.

In the past, the handling of ballast water has been essentially based on the need to achieve loading and unloading of cargoes in the most expeditious and safe way (consistent with a pre-established ballasting/deballasting plan) with little regard for the local environmental conditions. As a result of observations and research over the past decade, a series of precautionary management practices have been developed to assist in minimizing the risks of organism invasion (Carlton et al. 1995; AQIS 1998; Rigby 1994). Attention to these precautionary management practices during ballasting or deballasting in some
cases may provide a proactive approach that will be much simpler and more cost effective than one of the treatment options.

In principle, these techniques are aimed at minimizing the risks of the uptake of organisms, thereby reducing the quantity discharged and the probability of survival and establishment. Some of the main options that have been suggested are briefly outlined below.

**Minimization of ballasting during presence of target species**

Some organisms proliferate in a particular location at specific times, and avoidance of ballasting at these crucial times can minimize the number of organisms taken into ballast tanks. For example, clearly visible blooms of toxic algae could be avoided (Hallegreaff and Bolch 1992). These blooms are often limited to relatively short periods, especially during crucial periods when, for example, permanent resting cysts are present in the water column.

**Minimization of ballasting at night**

Many benthic species rise in the water column at night (Carlton et al. 1995) therefore avoidance of ballasting at these times may be beneficial.

**Minimization of ballasting in areas where sewer and industrial discharges occur**

Human pathogens may be discharged in some port locations where ballasting takes place.

**Minimization of ballasting in global hot spots**

This approach, suggested by Carlton et al. (1995) is similar to the first option and suggests that it may be possible to identify (via an international advisory network) regions where ballast water ought not to be taken on or where hot spots specific to a particular species exist.

**Minimization of sediment uptake in shallow ports or dredging areas**

Sediments present in ballast water during ballasting can present a problem in some ships, as they may settle in some of the ballast tanks and provide a habitat for organisms. Many large bulk carriers ballast in deep ports and this is less of a problem except perhaps in periods of high rainfall. However, it can be a cause for concern in shallower ports with minimum under-keel clearance. There are many aspects of sediment behavior that are not well understood, and further work is required to identify more clearly the true role that sediments play in the translocation of organisms. In some cases, although sediment may be present in ballast tanks, it is not necessarily discharged at the time of deballasting. Suctioning from high in the water column may assist in minimizing sediment uptake in some locations (Taylor 1996).

**Confinement of ballast to specific tanks**

Some ships have the capability of retaining all or part of the ballast water in non dedicated tanks that can be later discharged at sea when alternative water is taken into other tanks (Rigby 1994).

The practicality and effectiveness of some of these management options are quite limited as the ship’s Master often has little scope to vary ballasting times or patterns, as this needs to be synchronized with unloading schedules. It is also sometimes necessary to ballast and deballast within the same port, so the ability to select locations and times is again limited. Some ship’s schedules change on leaving a particular port, and the ship eventually ends up in a port different from that originally planned. These types of changes may have a bearing, in particular, on the effectiveness of the strategy of avoiding hot spots.

**Combined management strategies**

A combination of one or more of the above options, together with a number of other procedures, has formed the basis for overall integrated management strategies that have been suggested or included in guidelines introduced by various countries. The AQIS guidelines (AQIS 1998), for example, suggest that a number of the above options be adopted (wherever appropriate) in addition to the use of ballast exchange or some other treatment option and a consideration of the risk associated with discharging the ballast water in the deballasting port. The latter should take into account the conditions existing in the ballasting and deballasting ports for the target organisms of interest. The computerized DSS currently under development by AQIS will take all of these components (together with a more detailed assessment of biological, social, and management risks) into account. Carlton et al. (1995) have recommended a series of procedures based on consideration of the above precautions together with
considerations of ballast exchange at sea, backup zones for vessels that have been unable to exchange at sea, some form of risk assessment, and quarantine procedures for vessels identified as having high risk.

TREATMENT OPTIONS

A number of treatment options have been suggested as potential candidates either to completely kill or to significantly reduce the total number of organisms or the number of species present in the ballast water (Carlton 1990; Rigby et al. 1991; Rigby 1995; NRC 1996). These suggested treatments in most cases are essentially based on technologies or processes currently in use for industrial or domestic water treatment, and may not be effective or appropriate for treatment of ballast water. Only limited laboratory or ship-based trials have been undertaken to assess their effectiveness.

As distinct from some of the conventional processes, which are carried out in purpose-built equipment where design and operating conditions can be closely controlled, effective treatment of all the ballast water on a ship presents a range of differing problems. A typical “Cape Size” bulk carrier, such as the BHP-owned Iron Whyalla, with a loaded deadweight of 141,475 mt carries some 50,000 mt of ballast water in 10 sets of topside and double-bottom tanks as well as a forepeak and afterpeak tank. Indeed, each of the double-bottom tanks contains some 50 or so separate compartments (each open to the adjacent compartment for access and water flow); the whole ship contains many hundred small separate compartments.

Ballasting often takes place with both ballast pumps operating at a combined flow rate in the vicinity of 4,000 mt hr⁻¹. The internal construction of the tanks is complex, with a range of longitudinal, stiffener, and side-frame steel sections to maintain the ship’s strength. The tanks are suitably placed to maintain the stability of the ship. The consequence of this variety of tanks and structural and ballast water piping arrangements is that access to individual tanks and the ability to undertake specific treatment options in a controlled manner may be limited. Treatment processes can potentially be undertaken during ballasting, during the voyage, or while the ship is deballasting.

Table 1 lists the main potential treatment options that have been suggested. For the purposes of this discussion, ballast water exchange options have been included in the treatment options rather than in the management options, as the process does involve a change in the contents and composition of the water in the tanks. Special attention will be given to those options that are currently in use, have the most potential to be adopted for widespread use, or are being tested or demonstrated at present.

**Table 1. Possible options for ballast water treatment**

<table>
<thead>
<tr>
<th>Physical</th>
<th>Biological chemical or other</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ballast water exchange/ salinity increase</td>
<td>Ultraviolet irradiation</td>
</tr>
<tr>
<td>Heating/exchange</td>
<td>Ultrasound</td>
</tr>
<tr>
<td>Filtration/separation</td>
<td>Electrical discharge</td>
</tr>
<tr>
<td></td>
<td>Oxygen deprivation</td>
</tr>
<tr>
<td></td>
<td>Chemicals</td>
</tr>
<tr>
<td></td>
<td>ozone</td>
</tr>
<tr>
<td></td>
<td>chlorination</td>
</tr>
<tr>
<td></td>
<td>organic acids</td>
</tr>
<tr>
<td></td>
<td>copper/silver systems</td>
</tr>
</tbody>
</table>

Ballast water exchange

The exchange of original ballast water with ocean water in some form or other serves as the basis of control measures being utilized by several countries and is currently the only treatment option being used by the shipping industry. The basis of this form of treatment is that water from the deep ocean (generally considered to be free of the organisms of concern) is exchanged for the original water taken on during ballasting. The near-surface-dwelling organisms of the deep ocean form a group quite distinct from those organisms living in coastal waters where ballast water is first taken on (Carlton 1990).

In addition to exchanging all or part of the original water and organisms, this option can be effective as a natural biocide by increasing salinity levels in brackish waters to a point where some fresh water species are not able to survive. This form of treatment is the basis of the exchange controls on ships entering the St. Lawrence Seaway in North America in an attempt to control the spread of *D. polymorpha*.

The effectiveness of ballast exchange in replacing the original water and organisms will depend on the efficiency of the exchange, together with the exchange considered necessary to have the desired effect. For example, an increase in salinity will not generally require complete exchange of the ballasted
Table 2. Efficiency of water exchange for various ocean exchange options.

<table>
<thead>
<tr>
<th>Option</th>
<th>Mode of Exchange</th>
<th>% Water Exchanged</th>
<th>Indicative cost(^2) cents/mt</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Continuous flushing, 0.5 tank volume</td>
<td>39.3</td>
<td>0.8</td>
<td>Rigby &amp; Hallegraeff 1994</td>
</tr>
<tr>
<td>2</td>
<td>Continuous flushing, 1 tank volume</td>
<td>63.2</td>
<td>1.5</td>
<td>&quot;</td>
</tr>
<tr>
<td>3</td>
<td>Continuous flushing, 2 tank volumes</td>
<td>86.5</td>
<td>3.1</td>
<td>&quot;</td>
</tr>
<tr>
<td>4</td>
<td>Continuous flushing, 3 tank volumes</td>
<td>95.0</td>
<td>4.6</td>
<td>&quot;</td>
</tr>
<tr>
<td>5</td>
<td>Continuous flushing, 4 tank volumes</td>
<td>98.2</td>
<td>6.1</td>
<td>&quot;</td>
</tr>
<tr>
<td>6</td>
<td>Empty / refill (10 mt residual per cb tank)</td>
<td>99.8</td>
<td>1.5</td>
<td>Calculated</td>
</tr>
<tr>
<td>6a</td>
<td>(calculated for 50 mt residual water)</td>
<td>99.2</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Non-dedicated tanks empty / refill</td>
<td>100</td>
<td>1.5</td>
<td>Rigby 1994</td>
</tr>
<tr>
<td>8</td>
<td>Empty/refill</td>
<td>95.0</td>
<td>1.4</td>
<td>Miller 1998</td>
</tr>
<tr>
<td>9</td>
<td>Dilution/flushing</td>
<td>90.0</td>
<td></td>
<td>IMO MEPC1996</td>
</tr>
<tr>
<td>10</td>
<td>Sequential empty / refill</td>
<td>&gt;99</td>
<td>≈4.5</td>
<td>Wonham et al. 1996</td>
</tr>
<tr>
<td>11</td>
<td>Continuous flushing / heating</td>
<td>&gt;99</td>
<td></td>
<td>Rigby, Hallegraeff and Sutton 1998</td>
</tr>
<tr>
<td>12</td>
<td>Ocean exchange for salinity increase of brackish water; (ocean 35‰, brackish 15‰)</td>
<td>75</td>
<td>1.2 (empty / fill)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.8 (flush)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(ocean 35‰, brackish 5‰)</td>
<td>83</td>
<td>1.3 (empty / fill)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2.4 (flush)</td>
<td></td>
</tr>
</tbody>
</table>

\(^2\) based on a typical Cape Size bulk carrier carrying 50,000 mt ballast water (fuel costs estimated for diesel fuel 35c/lt) assumed no gravity filling/emptying.

Water (see Table 2, options 12, 12a), whereas the elimination of all original organisms would require complete replacement of all of the ballasted water (and sediments).

Two basic options exist for ocean exchange as shown in Figure 1 (Rigby 1994; Rigby and Taylor 1994). Reballasting is an effective way of replacing the original water with fresh ocean water. The efficiency of displacement will depend on the design of the ship's ballast tanks, quantity of water pumped and the pumping system design. Typically, this efficiency will vary in practice from 90-99.8% (Table 2, Figure 2). The lower efficiencies result from higher quantities of water remaining in the tanks after emptying. In many ships, such as the Iron Whally, secondary stripping using an ejector system can reduce this quantity to quite low amounts.

One of the potential hazards associated with this mode of exchange is that safe limits of bending moments and stresses on the ship can be exceeded in some cases (Rigby and Hallegraeff 1994). A sequential procedure where tanks are emptied and refilled in a defined sequence can assist in minimizing excessive stresses and bending moments (AQIS 1993a). It is essential that any of the ocean-exchange options be undertaken only if safe conditions can be maintained. Ultimate responsibility for the safety of the ship resides at all times with the ship's Master, and use of procedures where the safety of the ship and its crew may be affected should be approved by the Classification Society and the Flag State Administration.

Ballast exchange, or continuous flushing, avoids the problem of exceeding safe bending moments or stresses, since the tanks remain full at all times. The efficiency of water exchange of this option depends on the number of tank volumes exchanged (Rigby and Hallegraeff 1994; Table 2, Figure 2). Typically, an exchange equivalent to 1 tank volume will result in approximately 63% of the original water being replaced, whereas an exchange equivalent to 3 tank volumes will replace approximately 95% of the original water (Table 2, Figure 2). The efficiency of water exchange using this technique is lower if the ship is not at sea (for example, in a port), as the mixing is less efficient (Rigby and Hallegraeff 1994).

Reballasting compared to ballast exchange is generally more cost effective and can achieve a higher level of original ballast replacement in a shorter time. However, safety restraints may often dictate use of
the ocean exchange option. A combination of both reballasting and ballast exchange may be appropriate for some ships, especially where ship stresses are of concern when emptying some specific tanks (Rigby and Hallegraeff 1994).

It is noted that not all ships will be able to carry out the ballast exchange option as there may be no provision on the ship for overflow of the water. Minor modification to facilitate this option in new ships would not be of serious concern in new ship designs. Modifications to the basic flushing arrangements originally suggested by Rigby and Hallegraeff (1994) using alternative piping arrangements are possible (Armstrong 1997; IMO MEPC 1996, 1998), and may result in slightly different efficiencies of exchange. It needs to be pointed out, however, that differences in ballast tank, piping, and pumping designs are likely to have a much bigger influence on the efficiency than the superficial improvements in efficiency that are likely to result from these modifications.

An interesting option, currently being practiced by one shipping company, involves a 120,000-dwt bulk carrier and the use of dedicated and non-dedicated tanks to completely eliminate the original ballast water (Rigby 1994). In this case, the original ballast water (35,000 mt) is taken on in the Nos. 2, 3, 5, 7, and forepeak and afterpeak tanks. Once at sea, in an appropriate area, tanks Nos. 1, 4, and 6 are filled while the original tanks are emptied sequentially. The overall result is that none of the original water is discharged in the receiving port (Table 2, Figure 2, option 7), thus giving a 100% solution to possible organism translocation. Once again it needs to be stressed that this option is only likely to be possible on a limited number of ships.

The operating cost of carrying out ballast exchange is essentially that of the additional fuel required to operate the generators and pumps over the period of exchange. Table 2 and Figure 2 show some indicative fuel costs based on a typical Cape Size bulk carrier carrying 50,000 mt of ballast water, assuming a cost of $3.50/liter. Additional pump maintenance costs for the period have not been included. These costs do not take into account any additional costs that might be incurred by personnel working outside normal hours or for delays that could be involved if the ship was required to carry out exchange other than during its regular voyage route. These costs can be very substantial and

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**Figure 1.** Basic options for ocean exchange of ballast water.

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**Figure 2.** Efficiency and cost of ocean exchange for various options.
need to be borne in mind when developing overall strategies.

The efficiency of removal of organisms as distinct from ballast water is a complex issue, which will be affected by the nature and behavior of organisms in the tanks, the design of tanks, mixing within the tanks, and the types and behavior of sediments. For example, some fast-swimming zooplankton could feasibly remain after several tank volumes had been replaced, as indicated by recent sampling studies on the *Iron Whyalla* (Sutton et al. 1998).

Shipboard-based microscopic examination of organism removal during ballast exchange and heating trials on the *Iron Whyalla* showed that the efficiency of removal of phytoplankton from the water was similar or higher than for water exchange (Rigby and Hallegraeff 1994; Rigby et al. 1996b). Flushing trials by Ruiz and Hines (1997) in wing tanks showed a 60% water exchange on the basis of salinity and less than 90% on the basis of coastal plankton communities. In another trial, the exchange of 3 tank volumes resulted in water exchange efficiencies of 70-100% on the basis of salinity and greater than 95% on the basis of the presence of coastal organisms. In a recent trial undertaken by Brazil on the product carrier M/V *Lauras*, a water exchange efficiency of 90% was achieved with a phytoplankton exchange of 96%. Chlorophyll a exchange was estimated as 86% (IMO MEPC 1998). Many other studies showing survival of organisms have been reported following ballast exchange in some form or other; however, in many cases there has been no quantitative assessment of actual ballast exchange and so it is difficult to compare differences between water exchange and biological exchange. For example, Locke et al. (1993), using freshwater zooplankton and salinity as indicators (for ships originating from fresh and brackish water ports), estimated that for 24 vessels entering the Great Lakes region the efficiency of zooplankton exchange was 67% and for water exchange was 86%.

The significance and role of sediments in relation to ballast exchange has been poorly researched. Analyses of sediments removed from tanks have identified the presence of harmful organisms. For example Hallegraeff and Bolch (1992) have reported the presence of toxic dinoflagellate resting spores in various types of sediments. It is feasible for sediments to remain in ships for many years. However, in many ships sediment is confined to areas well away from locations where the main flow of water occurs and hence may not play a significant role in organism dispersal. Work currently in progress is aimed at examining some of these effects in more detail (Rigby et al. 1999a).

While ballast exchange is currently the primary option available to ship’s Masters for treatment of ballast water, there are some limitations and potential disadvantages as far as organism translocation is concerned. For example, MacDonald and Davidson (1995) found that reported ballast exchange increased the diversity of diatoms and dinoflagellate species during trips from mainland Europe to Scotland. These observations illustrate that caution needs to be exercised in assessing the most appropriate management or treatment option that might be used. Given the fact that many organisms do not survive on international voyages (Rigby and Hallegraeff 1994), it might be more appropriate in some cases to rely on natural mortality as a means of minimizing the risks rather than introducing a new community via ballast exchange.

**Ballast water heating and flushing**

The potential for inactivating toxic dinoflagellate cysts and killing other organisms in ballast water by heating has attracted recent interest as an environmentally responsible and potentially cost-effective treatment option. Initial laboratory work (Bolch and Hallegraeff 1993) indicated that heating *G. catenatum* dinoflagellate cysts to temperatures of 40-45°C for very short periods of time (30-90 sec) resulted in death. Lower temperatures at these short treatment times were less effective in killing the organisms.

Waste heat from a ship’s main engine, which is currently pumped overboard as a waste product, can potentially provide a cost-effective source of heat. However, if this option is to be used, heating needs to take place during transit, as the ship’s engine is not usually in operation during ballasting or deballasting. An analysis of available heat on the *Iron Whyalla*, indicated that the most appropriate means of utilizing this heat would be to flush the rejected hot ocean water (approx. 42°C) through the ballast water tanks in sequence, allowing the excess water to overflow from the ballast tanks. In addition to heating the ballast water, the flushing effect of the hot water would also significantly reduce the amount of originally ballasted water (and organisms) present at the end of the heating/flushing period.
A preliminary biological examination of this oceanic water heated by the engine’s cooling system on a voyage on the Iron Whyalla (Rigby and Hallegraeff 1994) showed that no phytoplankton or zooplankton survived, suggesting that treatment in this manner had potential. However, without significant modification to the main ship’s engine and waste-heat-recovery systems, there is insufficient heat available to reach a uniform ballast water temperature of 40°C in all tanks. Temperatures in the vicinity of 35-38°C are likely to be possible (after 24 to 30 hr flushing of each tank) on a voyage from Japan to Australia.

On the basis of these data, a series of further experimental tests (Rigby 1994) identified that most phytoplankton algae tested including Skeletonema costatum, dinoflagellates Amphidinium carterae, G. catenatum and Alexandrium catenella, and the golden-brown flagellate Heterosigma akashiwo, tested in the vegetative stage could be readily killed at temperatures as low as 35°C and treatment times in the range of 30 minutes to several hours. In addition, significant mortality was also achieved with G. catenatum and A. catenella cysts using longer incubation times (several hours) at temperatures as low as 35 to 37.5°C, with total mortality achieved at 38°C after 4.5 hr.

In order to test the practicality and effectiveness of this treatment option, two shipboard trials on the Iron Whyalla were undertaken between Port Kembla in New South Wales and Port Hedland in Western Australia and between Mizushima in Japan and Port Hedland. It was necessary to install some additional piping and valves to enable these trials to proceed.

On-board microscopic observation of heated water samples (Rigby et al. 1999b) showed that none of the zooplankton (mainly chaetognaths and copepods) and only very limited original phytoplankton (mainly dinoflagellates) survived the heat treatment. The original organisms were reduced to flocculent amorphous detritus. Subsequent culturing efforts on the heated ballast-tank samples produced growth of only some small (5 µm) diatoms and colorless ciliates that are considered to be of little consequence. Although no toxic dinoflagellate cysts were present in the tanks, based on earlier laboratory experiments, it is probable that these would have been effectively killed by the temperatures achieved during the heating trial, since essentially all of the water reached 37-38°C.

In addition to the effects of heating, this approach is also very effective in exchanging the original ballast water at the same time. Observation showed that 90-99% of the original plankton taken on during ballasting was removed by flushing (Table 2, Figure 2, option 11).

The temperatures reached during these trials would be insufficient to kill bacteria such as cholera. It is possible to heat ballast water to higher temperatures, for example, by heat exchange with the high-temperature piston-cooling-water circuit, by injection of steam, or by heat exchange with hot flue gases (Edyvean and Snedden 1985; Sobol 1995). However, these options require circulation of water to and from the ballast tanks during the voyage, can potentially cause operational problems or lack the amount of energy necessary to heat all the water, and are therefore less attractive than the flushing option. Nevertheless, future ship designs could consider some of these options.

Heating of ballast water as described above also has the added advantage that organisms contained in sediments would also be subjected to these temperatures (in fact higher temperatures are experienced at the bottom of the tanks where the ballast water is pumped into the base of the tanks).

The heating/flushing option is best suited for international voyages where there is adequate time to heat all of the tanks. It would not be possible to do this on a short coastal voyage.

Very few ships would be able to undertake this treatment option without some modification to the ballasting piping arrangement. Nevertheless, the option could ultimately provide one of the more attractive options for future ballast water management in order to comply with international requirements.

Filtration and Hydrocyclones

Filtration of ballast water to separate unwanted organisms is an option that has attracted some interest, especially in the United States where a large-scale shipboard trial on the bulk carrier M/V Algonaith has been in progress for some time.

Many of the organisms of concern in ballast water could be removed by filtration. Filtration at around 50 µm would be effective for the removal of most of the zooplankton and 20-µm filters would remove dinoflagellate cysts. Filtration of sea water is used routinely in many applications, including off-
shore oil platforms. Problems have been experienced in these operations with filter materials becoming coated with lipids and mucilage from plankton (Edyvean and Snedden 1985). Recent improvements with filter technology involving continuously cleaning and backflushing filters have reportedly overcome some of these problems. Apart from the cost and technical performance of the filtration system, there are several other issues that need to be considered. These include, for example, the storage and handling of the concentrated sludge and the significance of sediments that may exist in the ballast tanks.

The Algonorth trial involves a deck-mounted containerized filtration test unit that treats ballast water held in one of the upper wing tanks which has a capacity of 220 m³. Multi-level filtration using different size filters is being investigated at water flowrates up to 400 mt per hr. The project involves both biological and mechanical testing protocols. Although detailed information on the costs of filtration will depend on the results of the trial, indicative increased freight costs between US 2-20 cents/mt have been suggested (Parsons et al. 1997).

Hydrocyclones have also been proposed as a means of separating organisms from ballast water. Initial work by Jelmert (A. Jelmert, pers. comm.) using a "Lakos" hydrocyclone, and more recently in conjunction with a Norwegian hydrocyclone manufacturer who has developed a new concept, has demonstrated an 80% removal efficiency at 7µm. It has been proposed that the concept would include an ultraviolet irradiation treatment step after the hydrocyclone. Further testing of the biological capacity and removal efficiency of the combined system under development is in progress.

Ultraviolet Irradiation

Ultraviolet (UV) radiation is effective in destroying a range of microorganisms and is used routinely in the treatment of industrial water. However, its application for removing or inactivating many of the higher organisms and cyst stages of protozoa, microalgae, and macroalgae of interest in ballast water is yet to be demonstrated. UV radiation was shown to be ineffective for inactivation of six species of dinoflagellate cysts (Montani et al. 1995). These experiments involved placing the organisms under a lamp for a measured period but did not measure the light intensity. Oemcke (1998a) demonstrated that UV can be effective for inactivation of the cyst-producing dinoflagellate Amphidinium sp. Photoreactivation has been shown to be disabled by storage in ballast tanks after irradiation, and elevated temperatures increase the inactivation. Irradiation and dark storage were shown to be effective for disinfection of G. catenatum vegetative cells, but initial tests with cysts indicate that inactivation will be much more difficult (Oemcke 1998b).

Some of the issues that need to be addressed in assessing the potential use of UV irradiation for long-term ballast treatment include fouling of the UV quartz sleeve and the attenuating effect of sediments in the water (probably requiring pre-treatment by filtration at 20-30 µm). Oemcke and van Leeuwen (1998) have recommended a pilot-scale demonstration of combined filtration and UV irradiation so that the large-scale feasibility and costs can be assessed.

Accurate costing of this and other potential combined treatment options will not be possible until further work is completed. However, in order to gain an appreciation of the potential costs of some of these options for comparison with current practices involving ocean exchange, it is useful to examine one possible scenario. Previous work for treatment of ballast water at 4,000 mt hr⁻¹ involving separation (AQIS 1993b), together with comments from various workers associated with hydrocyclone and ultraviolet irradiation treatment, would suggest that the capital costs associated with retrofitting this type of equipment could be in the vicinity of US $2-2.5 million.

If this cost is considered for a bulk carrier operating on an international route, say from Australia to Japan (with a voyage round trip time of approximately one month) then it would discharge ballast water 12 times per year. If a capital recovery factor of 0.15 is assumed (interest rate of 8% over a 10-yr period) the capital cost component of the treatment (for 50,000 mt of ballast water) would be US 50-62.5 cents/mt ballast water. Operating costs would be in addition to the capital cost component. To put this cost into perspective, it needs to be compared with the costs for ballast exchange noted previously of US 1.4-4.5 cents/net (noting that these costs do not include a capital component).

Ultrasound

Ultrasound (using frequencies in the range from 15-100kHz) can destroy micro-organisms in water by
means of localized mechanical stresses resulting from cavitation (Shankle and Riech 1995). Although some success has been achieved killing _D. polymorpha_ veligers, it was concluded that such a system would not be practical for large-scale power plant intake application (NRC 1996). Given the technical uncertainties about the likely effectiveness of ultrasonics for killing organisms of interest in ballast water, together with the problems and cost associated with scaling-up existing systems to the size required for large ships, it appears unlikely that this option will become significant as a ballast water control measure.

**Electrical Shocks and Pulses**

Electric shock experiments by Montani _et al._ (1995) using 100 Volts AC for 5 sec were found to inactivate dinoflagellate cysts. Bolch and Hallaegraeff (1993) achieved inactivation of _A. catenella_ cysts with applied voltages greater than 5 V/cm, but 7% _G. catenatum_ cysts survived after treatment at 7.5 V/cm. However, this latter work demonstrated that the effect was due to the generation of chlorine and an increase in temperature rather than the electric shock.

Various forms of electric pulses have been demonstrated to either kill or stun brine shrimp, _Artemia salina_. Initial investigations with dinoflagellate cysts have not been encouraging and it appears unlikely that this option will attract much interest for large-scale ballast water treatment.

**Chemicals and Other Options**

A number of other biocide and chemical treatments have been suggested as potential candidates to kill ballast water organisms. At the current stage of demonstration and development, all of these have been rejected based on ineffectiveness, practicality, cost, or effect on the environment. Some brief comments concerning a selection of these options follow.

Ozone is used extensively for disinfection of fresh water; however, recent work by Oemcke and van Leeuwen (1998) has suggested that ozone is unlikely to be appropriate for ship board treatment of ballast water due to the possibility of increased corrosion and the difficulty in maintaining an effective disinfection residual as a result of the presence of sediments and dissolved iron.

Chlorine and hydrogen peroxide are both effective for destruction of some ballast water organisms, including dinoflagellate cysts (Rigby _et al._ 1993; Bolch and Hallaegraeff 1993). However, the high concentrations required to provide effective treatment mean that the costs would be prohibitive for the large quantities of ballast water involved. Problems associated with the safety and residual concentrations of chlorine also make these options unattractive.

Recent work by Voigt and Gollasch (1998) has shown that low concentrations (50 ppm) of a peroxide based liquid formulation involving specific activators have been effective in treating larval and adult stages as well as resting stages of _A. salina_. Further research work is in progress to pursue this treatment option.

Other chemicals including bromine, iodine, and organic acids (such as glutaraldehyde, glycolic acid and paracetic acid) have been suggested. While these chemicals are not uncommon in laboratory use for disinfection, their efficiency and use for treating ballast water remains questionable.

A synergistic combination of copper and silver ions has been used in hospital water systems for the control of bacteria. Although suggested as a possible candidate for ballast water treatment, tests carried out by Lloyd's Register (1995) on ballast water organisms showed that neither bacterial nor phytoplankton viability appeared to be significantly affected by the treatment.

A reduction in dissolved oxygen levels (by injection of nitrogen or by use of an oxygen scavenger chemical) although effective for starfish larvae, is ineffective for killing _Undaria pinnatifida_ spore (Mountfort 1997). Dinoflagellate cysts are known to survive for long periods under anaerobic conditions (Anderson _et al._ 1988). This option has therefore not been considered as a serious possibility for use in ballast water management.

**Conclusions**

A number of precautionary management practices have been developed to minimize the uptake of organisms in the water during ballasting. While these practices can provide a proactive approach that is much simpler and more cost effective than other treatment alternatives, variations in local conditions at the time of ballasting and practical limitations mean that the overall effectiveness of management options alone is somewhat limited. Nevertheless, an understanding of the possible options, and imple-
mentation where appropriate will form an important part of the overall ongoing strategy to minimize the spread of nonindigenous aquatic organisms.

Several treatment options aimed at killing or removing the harmful organisms present in the ballast water are presently in use, or are being developed and tested for use in conjunction with the management practices.

Ballast water exchange at sea will continue to be the primary option for most ships for many years to come. However, safety and practical restrictions, together with limitations on suitable exchange locations, are likely to limit the universality of this option. Heating of the ballast water using waste engine heat is a promising and cost-effective option that is likely to gain increasing acceptance in the international arena in the near future.

Filtration and hydrocyclones coupled with a secondary treatment option such as UV irradiation are currently being tested at practical scales of operation. These options will be more costly than either ocean exchange or heating and the technical efficiency for removal of organisms is yet to be reported and overall effectiveness assessed.

Other alternatives, including the use of biocides or chemicals, have generally been excluded to date based on cost, effectiveness, practicality, or environmental grounds. However, ongoing research and development will continue to provide the necessary data and confidence to assess the effectiveness of these options.

**Literature Cited**


Carlton, J.T., D.M. Reid, and H. van Leeuwen. 1995. The Role of Shipping in the Introduction of Nonindigenous Aquatic Organisms to the Coastal Waters of the United States (Other Than the Great Lakes) and an Analysis of Control Options. National Sea Grant College Program/CT Sea Grant Project R/ES6, 213pp.


Sources of Unpublished Material

Jelmert, A. Institute of Marine Research, Austevoll Aquaculture, N-5392 Store, Norway.


IMO MEPC, (International Maritime Organisation, Marine Environmental Protection Committee), (1996) 38/13/2 -Brazil. IMO MEPC, (International Maritime Organisation, Marine Environmental Protection Committee), (1998)42/INF:14 -Brazil.


Development of an Aquatic Nuisance Species Barrier in a Commercial Waterway

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ABSTRACT: The National Invasive Species Act (NISA) of 1996 authorized the U.S. Army Corps of Engineers to carry out a demonstration study of an aquatic nuisance species dispersal barrier in the Chicago Sanitary and Ship Canal. The objective of the study is to slow or prevent the dispersal of invasive species via the canal. This century-old, man-made canal is the only aquatic link between the Mississippi River and the Great Lakes drainage and forms a two-way avenue for invasive species dispersal. The canal is used for transportation of freight between Lake Michigan and the Illinois Waterway, and to carry wastewater away from Lake Michigan, Chicago's drinking water supply. Recreational vessels frequent the canal, but it is not used for water skiing or swimming. No migratory species traverse this man-made canal; however, the barrier is expected to affect native as well as invasive species. A multi-agency advisory panel ensures representation of the myriad interests in the canal and development of the barrier. The panel members identified potential methods and recommended an initial approach. Due to the commercial uses of the canal and its importance to Chicago's drinking water, physical barriers and canal closure are not practical alternatives. The demonstration study will begin with installation of a micro-pulsed DC electric barrier designed to deter fish, rather than stun them. The study will add methods to target other species as funding allows. Monitoring of the barrier performance will help determine effectiveness of each method. Conceptually, the full-scale barrier will consist of a two-barrier, redundant system in a restricted reach of the canal. Construction of the electric barrier should begin in the late spring of 2000.

Key words: aquatic nuisance species, barrier, canal, dispersal, Great Lakes; Mississippi River, Chicago River.

INTRODUCTION

The Chicago Sanitary and Ship Canal (San-Ship Canal) forms the sole aquatic link between the Great Lakes and Mississippi River drainage basins. This important transportation corridor also stands as an open portal to invasive species presently inhabiting either the Great Lakes or the Mississippi River. To slow or stop the spread of invasive species between the Great Lakes and Mississippi River drainage basins, the U.S. Army Corps of Engineers (USACE) and other agencies are examining methods to create a dispersal barrier in the San-Ship Canal. The National Invasive Species Act (NISA) of 1996 authorized up to $750,000 for the Corps to carry out a dispersal barrier demonstration study in the Chicago Sanitary and Ship Canal. In fiscal year (FY) 1998, $500,000 was appropriated for this work; an additional $300,000 has been scheduled for the Corps in FY1999.

HISTORY OF THE CHICAGO RIVER

Originally, the Chicago River flowed into Lake Michigan (Figure 1). During wet seasons, a shallow wetland called Mud Lake connected the Chicago River and Des Plaines River. Mud Lake was navigable by canoe for a few weeks of the year. Joliet and other early explorers recognized the potential for creating a permanent aquatic connection between Lake Michigan and the Des Plaines River to facilitate the transportation of goods and travelers to and from the Midwest.

The Illinois Michigan Canal (IM Canal) was the first attempt to form a permanent waterway between Lake Michigan and the Illinois River. The IM canal was essentially the predecessor of the San-Ship Canal. The IM canal was operated by pumping water from the South Branch of the Chicago River 15 ft up into the headwaters of the canal. The pumping reversed the flow of the river for much of the year. Inflow from Lake Michigan improved water quality of the heavily polluted river and carried the contamination away from Lake Michigan, Chicago's drinking water. During wet periods, however, the river still

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flowed into Lake Michigan, tainting the City's water supply. When the Chicago Sanitary and Ship Canal opened in 1910, the flow reversal became essentially permanent. Pumping was no longer required to maintain flow through the canal. The elevation change between Lake Michigan and the Des Plaines River was sufficient to create a flow out of the lake.

Other rivers and canals now connect to the San-Ship Canal. Like the Chicago River, the Calumet River originally flowed into Lake Michigan. The Calumet River now connects with Saganashkee Slough to form the Cal-Sag Channel. Once complete, this connection reversed the flow in the Calumet River such that it flows out of Lake Michigan. There are three other connections between Lake Michigan and the San-Ship Canal. The North Shore Channel at Wilmette, Illinois helps maintain water quality in the north branches of the Chicago River. Both the Grand Calumet and Little Calumet River connect to the Cal-Sag Channel. All water from these various sources must pass through a single narrow reach near Lemont, Illinois where the canal cuts through native limestone. At this point, the 50-m wide and 7.5-m deep canal has perpendicular walls and a flat bottom (Figure 2).

**Figure 1.** Configuration of the Chicago and Calumet rivers before and after development of the Sanitary and Ship Canal and Cal-Sag Channel.

**Figure 2.** Cross-section of the Chicago Sanitary and Ship Canal at the proposed barrier site.

**Water Quality and Flow**

Historically, poor water quality in the canal formed an effective barrier to inter-basin range expansion of Great Lakes or Mississippi River species. Over the last two decades, the Metropolitan Water Reclamation District of Greater Chicago has invested millions of dollars to improve wastewater treatment and water quality in the canal. The improvements have contributed to significant increases in dissolved oxygen and reduced ammonia-nitrogen. In turn, the diversity and abundance of fish species in the canal system have increased (Figures 3 and 4).

**Figure 3.** Water quality parameters in the Chicago Sanitary and Ship Canal and the Cal-Sag Channel, 1975-1995.
Table 1. Recent invasive species present in either the Great Lakes or the Mississippi River basins. * Species already found in Lake Michigan or the Calumet River.

<table>
<thead>
<tr>
<th>Great Lakes</th>
<th>Mississippi River</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spiny waterflea*</td>
<td>Striped bass Morone saxatilis</td>
</tr>
<tr>
<td>Bythotrephes cedrostrmi</td>
<td></td>
</tr>
<tr>
<td>Fishhook waterflea*</td>
<td>Hybrid striped bass* Morone saxatilis x M. chrysops</td>
</tr>
<tr>
<td>Cercopagis pengoi</td>
<td></td>
</tr>
<tr>
<td>Eurasian ruffe Gynocephalus cernus</td>
<td>Grass carp* Ctenopharyngodon idella</td>
</tr>
<tr>
<td>Round goby*</td>
<td>African spiny waterflea* Daphnia lumholtsi</td>
</tr>
<tr>
<td>Neogobius melanostomus</td>
<td></td>
</tr>
<tr>
<td>Tubenose goby</td>
<td>Black carp Mylopharyngodon piceus</td>
</tr>
<tr>
<td>Prorocentrum marmoratus</td>
<td></td>
</tr>
<tr>
<td>White perch* Morone americanus</td>
<td>Bighead carp Hypophthalmichthys nobilis</td>
</tr>
<tr>
<td>New Zealand mud snail</td>
<td>Potamocephalus antipodarum</td>
</tr>
<tr>
<td>Three-spine stickleback*</td>
<td></td>
</tr>
<tr>
<td>Gasterosteus aculeatus</td>
<td></td>
</tr>
</tbody>
</table>

The average annual discharge from Lake Michigan is fixed by court decree at cfs. This volume includes what is used for drinking water as well as water that leaks through breakwalls or passes during operation of the locks. Diversion gates at Chicago Harbor, O’Brien Lock and Dam, and on the North Shore Channel at Wilmette control the volume of Lake Michigan water diverted down the canal to maintain water quality. Depending on rainfall, there can be a ten-fold variation in flow volume and velocity in the canal. Flow volume ranges from 2000 to 20,000 cfs with corresponding velocities of 0.5-5 ft per sec.

Species of Concern

Today the Chicago Sanitary and Ship Canal is a two-way avenue for inter-basin spread of invasive species. As occurred with the zebra mussel (Dreissena polymorpha), other invertebrates and fish in the Great Lakes can spread into the Mississippi basin. Native and introduced species in the Mississippi drainage can spread into Lake Michigan and the other Great Lakes. These invasive species will directly compete with and could prey upon existing biota.

Table 1 lists invasive aquatic species that could spread or are in the process of spreading from the Great Lakes or the Mississippi basin to invade a new, major drainage. Hybrid striped bass (Morone saxatilis x M. chrysops) are present in low numbers in Lake Michigan. Grass carp (Ctenopharyngodon idella) have been captured in Lake Calumet, only 7 mi from Lake Michigan and Daphnia lumholtsi, an African spiny water flea, has been found in the Calumet River. In 1999, a round goby (Neogobius melanostomus) was caught below the confluence with the Des Plaines River, at RM 290.25 downstream from the site identified for the demonstration study (P. Thiel, pers. comm.).

Boat Traffic on the Canal

These two major uses of the canal—commercial navigation and wastewater conveyance—constrain the dispersal barrier options. The barrier cannot physically close the canal and should not significantly interfere with barge traffic or water flow. At the location identified for the barrier study, approximately 50 percent of the flow is treated effluent.

In addition to conveying wastewater, the canal system is an important transportation corridor for freight and recreational vessels. Chicago Lock is the
nation's busiest, passing 50,000 to 60,000 vessels annually. The vast majority of the vessels are recreational and sightseeing craft. At O'Brien Lock, and farther downstream at Lockport, barge tows comprise a greater portion of the traffic (Table 2).

Due to the narrow width and perpendicular walls of the San-Ship Canal, the tows often navigate the canal by running the barges immediately along the wall. Insufficient structures extending out from the wall are subject to damage or removal as the barge passes. Structures substantial enough to fend off the barge as it moves along the wall could deflect the tow out into the channel potentially causing a collision.

**Advisory Panel**

The diversity of uses and users of the canal system required stakeholder involvement in the development of the invasive species dispersal barrier for success of the project. The USACE formed a Dispersal Barrier Advisory Panel. Currently, panel members represent more than 25 federal, state, regional, municipal, commercial, and environmental groups or agencies and academia (Table 3). Expertise on the panel includes field and research biologists, engineers, regulators, barge operators, and commercial water users.

The panel members characterized an ideal barrier as cost effective, quick to implement, protective of public health, environmentally sound, having little residual downstream effect, continuous, fail safe, redundant, broad spectrum, applicable to other systems, and providing long-term effectiveness. They then listed types of barriers that could be effective against an array of aquatic species ranging from zooplankton to fish. The list included chemicals (toxicants and oxidants), nitrogen stripping, low dissolved oxygen, chlorine, electricity, acoustics, lights, hydraulic jets, weirs, and screens. The panel considered modifying operational aspects of the canal system such as dams, closure of the canal, and flow reversal. The panel also considered the effectiveness of biological controls such as predators, disease, and parasites.

Potential methods were ranked based on available technology, predicted or known organism response, and feasibility. Commercial navigation and wastewater uses of the canal system essentially preclude physical barriers such as screens or weirs and flow reversal.

**Conceptual Approach and Recommended Strategy**

The panel recommended the barrier use a redundant, “fail-safe” approach. Figure 5 illustrates the proposed barrier concept. The two independent barrier systems would be placed some distance apart, perhaps 300-500 m or more to avoid interference and allow sampling and monitoring of the canal reach between the two arrays. This canal reach could

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**Table 2.** Waterborne traffic in the Chicago Sanitary and Ship Canal, Cal-Sag Channel and Des Plaines River during 1995. Total includes tows, passenger boats/ferries, recreational vessels, cargo vessels, US Government vessels and contractors, commercial fishing boats. Other excludes the recreational and tow vessel numbers. Source: USACE 1996

<table>
<thead>
<tr>
<th>Lock</th>
<th>River</th>
<th>Vessels</th>
<th>Recreational</th>
<th>Tows</th>
<th>Other</th>
<th>Kilotons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chicago</td>
<td>Chicago</td>
<td>52,983</td>
<td>38,790</td>
<td>118</td>
<td>14,075</td>
<td>201</td>
</tr>
<tr>
<td>O'Brien</td>
<td>Cal-Sag</td>
<td>21,883</td>
<td>17,517</td>
<td>3,746</td>
<td>620</td>
<td>12,849</td>
</tr>
<tr>
<td>Lockport</td>
<td>Des Plaines</td>
<td>4,102</td>
<td>1,103</td>
<td>2,705</td>
<td>294</td>
<td>14,865</td>
</tr>
</tbody>
</table>

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**Table 3.** Membership of the Chicago Sanitary and Ship Canal Aquatic Nuisance Species Dispersal Barrier Advisory Panel.

<table>
<thead>
<tr>
<th>Federal</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td>U.S. Army Corps of Engineers</td>
<td>Illinois Department of Natural Resources</td>
</tr>
<tr>
<td>U.S. Fish and Wildlife Service</td>
<td>Illinois Natural History Survey</td>
</tr>
<tr>
<td>U.S. Environmental Protection Agency</td>
<td>Office of Water Resources</td>
</tr>
<tr>
<td>U.S. Geological Survey</td>
<td>Illinois Environmental Protection Agency</td>
</tr>
<tr>
<td>- Biological Resources Division</td>
<td></td>
</tr>
<tr>
<td>U.S. Coast Guard</td>
<td>Illinois Pollution Control Board</td>
</tr>
<tr>
<td>Great Lakes Fishery Commission</td>
<td>Illinois-Indiana Sea Grant</td>
</tr>
</tbody>
</table>

**Regional & Industry**

| Metropolitan Water Reclamation District of Greater Chicago | Commonwealth Edison |
| Illinois River Carriers Association | Smith-Rooit, Inc. |
| Michigan State University | DuPage County Forest Preserve |
| Loyola University | Great Lakes Commission |
| Great Lakes Sportfishing Council | Northeastern Illinois Planning Commission |
| University of Windsor | Friends of Chicago River |
| Minnesota Department of Natural Resources | Canal Corridor Association |
| Wisconsin Department of Natural Resources | |
eventually provide an area for application and detoxification of chemical controls.

The long-term objective of the barrier demonstration is to create a barrier that is that is effective against all types of organisms. Nonplanktonic organisms will likely be easier to deter than planktonic ones. Organisms that are strong swimmers could sense the presence of the barrier; the organism would then return in the direction from which it came. A planktonic organism would merely be flushed through the barrier, regardless of the level of discomfort. Methods that deter fish may not be effective against zooplankton, so a variety of barrier approaches will have to be employed. It is expected that native species will be affected as well as invasive species.

It will be easier to obtain a permit for non-chemical approaches than for methods that affect water quality. In the near term, barrier methods used in the demonstration study will rely on fish behavioral response. The panel recommended application of chemicals as a stopgap measure or possibly for seasonal use only.

The demonstration study will occur in phases. The first phase will target active swimming organisms (fish), beginning with an electric barrier. Next, the study will examine methods that would complement the effect of the electric field, such as an acoustic or visual barrier, water jets, or a combination of methods. As various methods prove successful at the first location, they could be applied at the second barrier site. Over the long term, the study will investigate the potential for creating a barrier for planktonic organisms.

Construction of the barrier is scheduled to begin in 2000. The project will start with a Smith-Root, Inc. micro-pulsed DC electric array. Electric barriers of this type prevent upstream migration of lampreys in Great Lakes tributaries and confine vegetation-controlling Grass carp in Western irrigation canals. The electrodes will be railroad rails. Recessing the rails into the canal walls will avoid damage from barge traffic. The pulsators and back-up generator will reside in a small equipment shed on shore. The effect of the electric field will affect the entire water column and will extend about 7 m up and downstream from the array.

**Monitoring, Safety, and Next Steps**

Once the electric array is constructed, monitoring will assess the effect on fish at the barrier site. Fish present in the canal will be captured and tagged according to the location of capture, i.e., upstream or downstream of the array. The effect of the array on movement of the fish will be determined through recapture.

Due to the low voltage and direct current used for the barrier, electric shock is not a concern. A boy on an inner tube, a dog, and a horse have passed through the arrays in the irrigation canals without adverse effect. Signage and lights posted well in advance of the barrier site will warn of the presence of the barrier. Swimming and water skiing do not occur in the canal, but it is conceivable that a person could fall overboard near the array. Egress ladders or similar equipment installed in the canal walls will provide a means of exiting the water.

The study will continue investigating other barrier methods that will complement or, if proven effective, could substitute for the electric array. One attractive approach requiring further investigation involves an infrasound acoustic array. This method poses no safety concerns, is commercially available, and has been successfully used in Europe to guide fish past water intakes and canal openings. During development of the first barrier, potential sites for the second, redundant barrier will be identified.

**Conclusion**

If successful, the dispersal barrier will prevent the passive spread of invasive species via the Chicago Sanitary and Ship Canal. It will not control human-mediated spread of invasive species, for example, as can occur through bait bucket introductions. The barrier project is an important part of a comprehensive program to prevent the introduction and spread
of aquatic nuisance species throughout North America. However, education of recreational and commercial water users and cooperation among natural resource agencies, commerce, and the public are critical components for a successful nuisance species prevention program.

**Literature Cited**


**Source of Unpublished Materials**

Implementation of the National Invasive Species Act of 1996 (NISA)

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Key words: NISA, ballast water, regulation, U.S. Coast Guard, exotic species, nonindigenous species, aquatic nuisance species

BACKGROUND

I am going to discuss the background of the National Invasive Species Act and bring you up to speed on how we have arrived at the current situation.¹ We are still in the comment-and-review period of the proposed rule that was published April 10, 1998.

One of the major issues that we deal with is the definition of nonindigenous species, which are species transported to other than their native habitat. In the absence of natural predators or natural controls, they can often out-compete native species, reduce biodiversity, and become nuisance species. Most of you are already aware of many of the examples of nonindigenous species that have become issues nationally and internationally. The “poster child” for us has been the infestation of zebra mussels in the Great Lakes. We were warned as early as the 1920s that the zebra mussel was a potentially invasive species, but that invasion did not occur until the 1980s. The zebra mussel problem in the Great Lakes became the driving force behind most of the policy that was implemented in the late 1980s and early 1990s.

NON-INNOCIOUS Aquatic Nuisance Prevention and Control Act

In the late 1980s, Senator Glen proposed legislation that became the Non-Indigenous Aquatic Nuisance Prevention and Control Act (NANPCA) of 1990. NANPCA addressed the Great Lakes issue and called for a shipping study to see if this was a local or a national issue. Under NANPCA, we originally worked with the Canadian Coast Guard and issued voluntary guidelines for ballast water control management. We also worked with the International Maritime Organization (IMO) to try to come to an international resolution of this issue, which is not just a national problem.

In 1993, we promulgated mandatory regulations for the Great Lakes, requiring an open-ocean exchange or equivalent for all vessels carrying ballast water into the Great Lake system. The Great Lakes system is unique in that there is a bottleneck: all vessels entering the Great Lakes from outside the Exclusive Economic Zone (EEZ) must come through the St. Lawrence Seaway. Enforcement can be carried out at Massena, NY, between the locks on that seaway. NANPCA also provided funding for research, which many of you have already been involved with.

NATIONAL INFAMOUSpecies ACT

As a result of the shipping study and other issues that came to the forefront, such as finding cholera in the ballast water of ships in Mobile Bay in 1992 and the green crab infestations, the National Invasive Species Act (NISA) of 1996, which amended and modified NANPCA 1990, was issued. NISA requires the Coast Guard to promulgate voluntary guidelines for all vessels entering U.S. waters from outside the EEZ. By presidential proclamation, the EEZ is 200 miles from our coastline in most areas. As previously noted, we are in the comment-and-review portion of this proposed rule. If you wish to look at the comments, they are available on the docket management services website at http://dms.dot.gov/, docket number USCG-1998-3423. Originally, I was going to speak more about the proposed rule itself, but a lot cannot be released until the final rule comes out.

We are also working with the Aquatic Nuisance Species Task Force to develop voluntary guidelines.

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²Information in this paper current as of 1/1999
for recreational vessels. This is not just a problem with ships entering the United States: the interstate transport of recreational vessels affects a lot of our water bodies.

On the international level, we are participating in a working group within IMO. Currently, we have a proposed annex to the International Convention for the Prevention of Pollution from Ships, 1973, as modified by the Protocol of 1978 (MARPOL 73/78), that will address the aquatic nuisance species problem; a stand-alone treaty is also under consideration. One of the issues involves the measures it would take to bring it into effect. We would have to have 50% of the world’s shipping tonnage in support of it as an annex to MARPOL. The U.S. Congress has given its tacit approval to MARPOL, therefore both avenues of that instrument are being considered at this time. Copies of the draft annex to MARPOL are available. Please check the IMO Documents section of our webpage www.uscg.mil/hq/g-m/mso4/first.htm for information on how to obtain them.

We recognize that the technology to control or eliminate transport by ballast water is not yet available. We accept ballast water exchange as a control measure: it reduces the risk but does not eliminate it, and it is also not possible in all situations or for all classes of vessels. We have structural and stability concerns with some ships. We do not want them to crack in half and create a major oil spill or loss of life.

I do want everyone to keep in mind that while ballast water is a major path of introduction, it is not the only path. We are also looking at issues with the ship’s hull. Tributyltin (TBT) is a component of the paint used on ship hulls and does reduce the fouling on the hull, but TBT itself is of concern. When TBT paints are taken off, nonindigenous species may be transported. An international effort is underway to find replacements that are not as harsh to the environment.

We recognize there is no silver bullet for ballast water treatment. We would accept a toolbox approach in which a shipping organization could propose a ballast water control method and not be limited to just one technology or method.
The Aquatic Nuisance Species Act and the Marine Environment

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Key words: aquatic nuisance species, ANS Task Force, NISA, management plan

INTRODUCTION

The primary focus of this presentation is to highlight the Nonindigenous Aquatic Nuisance Prevention and Control Act of 1990 (amended as the National Invasive Species Act in 1996 or NISA) and how it applies to the marine environment. Prior to 1990, there were numerous scientists trying to get people to recognize that invasive aquatic species posed a serious problem. Although invasives were having serious economic and ecological impacts, very few people were paying attention. In the marine environment, prior to 1990, there were limited control activities taking place and very little research being conducted.

Starting slowly in the 1970s and 1980s, the voices of concern began getting louder. We began to see activities such as the control of sea lampreys in the Great Lakes and concerns about grass carp moving into the west. President Carter issued his Executive Order on exotic species, which also helped to increase awareness. The zebra mussel functioned as a poster child of sorts in that it was responsible for getting the attention that led to the passage of the Act. Not only was it causing serious environmental impacts, but was having substantial economic impacts to the water and power infrastructure in the Great Lakes.

If the impact had only been from an ecological perspective, we may not have been successful in getting Congress to pass the Act. The fact that zebra mussels shut down the water intake to the city of Toledo, Ohio, which ran uninterrupted for over 120 years, was certainly a factor in gaining attention.

Senator John Glenn, Ohio and his primary staff person, Allegra Cangelosi, are owed a debt of gratitude and thanks, as are other early invasive species pioneers who were responsible for developing the legislation. When the legislation was initially drafted, it focused on the Great Lakes, as invasives were viewed as primarily a Great Lakes issue. That language was broadened somewhat before the Act was passed and in the recent amendment to the Act, the National Invasive Species Act of 1996, the focus was broadened even more.

The Act is comprised of two primary components: the ballast water management component and the development of the Aquatic Nuisance Species (ANS) program. The ANS Program has three primary elements, prevention, detection, and monitoring, and control. The ballast water program includes the establishment of mandatory ballast water regulations in the Great Lakes, and a requirement for the Armed Services to have a ballast water management program. Additionally, the National Atmospheric and Atmospheric Administration (NOAA) and the Fish and Wildlife Service (Service) are coordinating a program to provide funding for demonstration projects for new technologies for ballast water management. There is currently a demonstration project underway in the Great Lakes to look at various technologies. Other studies that have recently been completed include the Ballast Exchange Study, that will soon be out in final form and available for public review. There is also a requirement under the Act to develop a research protocol to ensure that research done with invasive species is not a contributing factors to furthering their spread. Guidelines for recreational activities are also being developed to ensure that these activities do not contribute to the spread of aquatic invasives.

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A significant feature of the Act is the provision that provides for cost-share grants for States to implement State and Interstate ANS Management Plans. Currently five states have completed ANS Management Plans and about another dozen or so are in development. If we are successful in getting more states engaged in this issue we will certainly be more effective in trying to address the problems.

The ANS Task Force was established by the 1990 Act and held its first meeting in 1991. It is co-chaired by the Director of the Fish and Wildlife Service and the Administrator of NOAA. It is a coordinating entity that is comprised of federal agencies and ex-officio members. Its primary responsibility is to coordinate the implementation of the mandates or requirements of the Act. The U.S. Coast Guard has the primary responsibility to address the ballast water mandates. The Act specifically identifies the Fish and Wildlife Service, NOAA, the Coast Guard, the Environmental Protection Agency, the Army Corps of Engineers and the Animal and Plant Health Inspection Service (APHIS) in the Department of Agriculture as members. The State Department was added by consensus of the other Federal members to ensure that international aspects and components of the program were addressed.

The Act provides for ex-officio members to participate, initially specifying the Great Lakes Commission as a member. When the Act was reauthorized, other ex-officio members were added. The Lake Champlain Program, the Chesapeake Bay Program and the San Francisco Estuary Program were designated as ex-officio members during the reauthorization. When ex-officio members were originally invited, groups such as the American Water Works Association, and the American Public Power Association were invited to be members. These additions were primarily because the focus was on zebra mussels and the Great Lakes region. We are now going through a process of reviewing ex-officio membership to determine if we need to add to that membership looking at it from both an issue basis as well as a geographic basis.

From the beginning, the task force has functioned on a consensus basis. I think to date we have never had to vote on an issue. All of the Task Force meetings are open to the public and are usually held about three times a year. Our next meeting was held in association with the International Zebra Mussel Conference in Duluth, Minnesota. Many of the responsibilities of the Task Force are carried out through various committees. To address regional concerns, we have a Great Lakes Panel, a Western Regional Panel and are in the process of putting together a Gulf Coast Panel. Other committees have been established including a Brown Tree Snake Control Committee, a Risk Assessment Committee, and a Ruffe Control Committee. We are currently in the process of establishing a Green Crab Control Committee. These groups are responsible for developing control plans, and identifying potential funding to implement them. One of the early studies that was conducted by the National Research Council called "Stemming The Tide," began identifying a list of things that could be done to address some of the ballast water issues. Other things that have implications for coastal areas include the green crab control program, which is about to get up and running, and also a mitten crab control program.

As with many projects or legislation, finding adequate funding is always a problem. While the authorization level for the Act is around $33 million, only about 44% to date has been allocated to carry out the mandates of the Act. One of the difficulties from the very beginning was that each agency represented on the Task Force falls under a different sub-committees in the Congressional Budget process. Often, one agency will get funding and another agency will not. This situation has been especially difficult because much of the work is interrelated. With the potential of the new Executive Order on Invasive Species coming out, there should be stronger support by the administration to look at cross program budgeting. When the Task Force was initially established, very little funding was available and each agency contributed a staff person to participate. As the Task Force has grown and gotten more involved, many of the Federal agencies now are coming to the table with additional money. For example, NOAA is providing funding to the Task Force on an annual basis to be used to hire an outreach person. There are also other positions that the other agencies have provided to assist the Task Force in carrying out its responsibilities.

To summarize, a quote by E.O. Wilson expresses why we all should be concerned with invasive species: "extinction by habitat destruction is like death in an automobile accident, easy to see in excess. Extinction by invasion of exotic species is like death by disease. Gradual, insidious, requiring scien-
tific methods to diagnose.” The Secretary alluded to this in an earlier talk comparing it with the Exxon Valdez oil spill and what it did to raise the level of national attention. The invasive species issue is bubbling below the surface where it is often out of sight and out of mind. I believe the tide is turning and we are poised to move forward into a new decade where we will have increased opportunities to address the threat from invasive species.
Why Ballast Water Discharges Should be Regulated Under the Clean Water Act

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Key words: ballast water, clean water act, management

I. THE PLAIN LANGUAGE OF THE CLEAN WATER ACT REQUIRES NPDES PERMITS FOR BALLAST WATER DISCHARGES

The Clean Water Act (CWA) prohibits "the discharge of any pollutant by any person" except as in compliance with specified sections of the Act, including the permitting provisions of § 402. 33 U.S.C. § 1311(a). The phrase "discharge of a pollutant" is defined to include "any addition of any pollutant to the navigable waters from any point source." 33 U.S.C. § 1362(12). Vessels are specifically defined as point sources in the CWA. 33 U.S.C. § 1362(14).

Moreover, the CWA specifically includes "biological materials" in its definition of pollutants. 33 U.S.C. § 1362(6). The discharge of ballast water from vessels is a discharge of pollutants because ballast water is known to contain invasive plant and animal species as well as bacteria and viruses associated with human sewage. All of these pollutants qualify as "biological materials" within the meaning of the CWA.

Additionally, ballast water is likely to contain other pollutants, such as oil, chipped paint, sediment, and toxins contained in ballast sediment.

Under the CWA, vessels qualify as point sources. Accordingly, when they discharge pollutants, they are required to have National Pollutant Discharge Elimination System (NPDES) permits. Although EPA has purported to exempt "discharge[s] incidental to the normal operation of a vessel" from the requirement to obtain a permit, 40 C.F.R. § 122.3(a), nothing in the CWA gives EPA the power to create categorical exemptions. Natural Resources Defense Council v. Costle, 568 F.2d 1369, 1377 (1977) (Costle). While EPA is given substantial deference in interpreting the CWA, it cannot rely upon regulations that are clearly contrary to the express statutory requirements. Chevron v. Natural Resources Defense Council, 467 U.S. 837 (1984), City of Chicago v. Environmental Defense Fund, 114 S.Ct. 1588 (1994).

The CWA does contain certain limited exemptions relating to the need to obtain NPDES permits for ballast water and other discharges incidental to the normal operation of vessels. None of these exemptions can reasonably be construed as permitting the blanket exemption contained in 40 C.F.R. § 122.3(a). First, the CWA excludes incidental discharges from vessels made in the "contiguous zone" and the "ocean" from having to obtain an NPDES permit. 33 U.S.C. § 1362(12)(B). These terms have clear statutory definitions: the "contiguous zone" begins three miles from shore and extends seaward to twelve miles from shore; and the "ocean," is any portion of the high seas beyond the contiguous zone. 33 U.S.C. § 1362(9) and (10). Thus, the effect of this exemption is that incidental discharges (such as ballast water) made outside of three miles from shore are not required to have NPDES permits. It cannot, however, reasonably be construed as applying inside the three mile contiguous zone boundary.

Second, the CWA specifically excludes two types of discharges from its definition of "pollutants." 33 U.S.C. § 1362(6)(A). The Act states that neither discharges of "sewage from vessels or a discharge incidental to the normal operation of a vessel of the Armed Forces," are to be considered pollutants. Id. (emphasis added). As a result of the second aspect of this exclusion, discharges incidental to the normal operation of Armed Services vessels are not required to have an NPDES permit. However, this exemption is specifically limited to Armed Services vessels; EPA cannot reasonably expand it to apply to all vessels, as it has done in 33 C.F.R. § 122.3(a).

It is important to note that, in exempting both sewage discharges and incidental discharges from Armed Services vessels, Congress specifically provided alternative programs for control of such discharges under other sections of the CWA. See 33 U.S.C. § 1322(b) (addressing sewage discharges) and (n) (addressing incidental discharges from Armed Forces vessels). The fact that there is no similar statutory or regulatory provision, which addresses incidental, dis-

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Charges from non-Armed Services vessels under the CWA further highlights the Congressional intent that ballast water discharges be regulated under § 402 of the CWA.

The Act is clear that ballast water releases that contain biological materials qualify as point source discharges of a pollutant and that such discharges require NPDES permits under § 402. 40 C.F.R. § 122.3(a) runs directly counter to this plain statutory requirement and should therefore be repealed.

II. Existing Case Law Unequivocally Indicates that EPA Does Not Have the Discretion to Exempt Incidental Discharges from the Requirements of the CWA

In *Castle*, the D.C. Circuit addressed the question of whether EPA could exempt agricultural return flows from the requirements of the CWA. 568 F.2d 1369 (D.C. Cir. 1977). The court unambiguously stated that the EPA did not have the authority to exempt discharges from the requirements of § 402. Finding that § 402 permits were central to achieving the stated goals of the CWA, the court found that “[t]he wording of the statute, legislative history, and precedents are clear: the EPA Administrator does not have authority to exempt categories of point sources from the permit requirements of §402.” *Id.* at 1377; see also *NRDC v. U.S. E.P.A.*, 966 F.2d 1292, 1305 (9th Cir. 1992); *Carr v. Alta Verde Industries Inc.*, 931 F.2d 1055,1060 (5th Cir. 1991); *Sierra Club v. Abston*, 620 F.2d 41, 44 (5th Cir. 1980); and *U.S. v. Earth Sciences, Inc.*, 599 F.2d 368, 372 (10th Cir. 1979).

In reaching its result, the *Castle* court relied on both the language of the statute itself and its underlying legislative history. As noted by the court, the House Report addressed the effect of § 301 in the following terms:

Any discharge of a pollutant without a permit issued by the Administrator under section 318, or by the Administrator or State under 402 or by the Secretary of the Army under 404 is unlawful.

568 F.2d at 1374, citing H.Rep.No.92-911, 92d Congress, 2d Session 100 (1972), reprinted in Legislative History at 787. The court further noted that there were: innumerable [other] references in the legislative history in the legislative history to the effect that the Act is founded on the “basic premise that a discharge of pollutants without a permit is unlawful and that discharges not in compliance with the limitations and conditions for a permit are unlawful.”

*Id.* at 1375.

In promulgating 40 C.F.R. § 122.3(a), EPA acted in direct violation of the straightforward rule established in *NRDC v. Castle*, EPA has created a categorical exclusion in a statutory scheme that permits or none.

III. Benefits of Clean Water Act Regulation

Control under the CWA would have two components. First, EPA would be required to develop technology-based controls based on the “best available technology that is economically achievable” (BAT). Before EPA were to set this standard, the permit issuers (typically the states under the CWA) would be required to exercise their “best professional judgement” in trying to anticipate what the BAT standard would be when it were to come out. Thus, all ballast water dischargers would immediately become subject to technology-based controls.

As importantly, the permit issuers would be required to ensure—on a case-by-case basis—that the relevant dischargers would comply with water quality standards. Given that few (if any) states have water quality standards that directly address the issue of invasive species, the key short-term issue here would be compliance with the antidegradation policy.

Under this policy, no discharge can be permitted if it will impair any “existing use” of the relevant waterbody. 40 C.F.R. § 131.12. Existing uses are defined to include any species that have inhabited a particular waterbody since November 28, 1975. 40 C.F.R. § 131.3(e). Thus, under the antidegradation policy, the permit issuer would be required to perform an analysis—as a precondition to permitting a discharge of ballast water to occur—that would be designed to preclude the possibility that any invasive species present in the ballast water might outcompete any existing (i.e., native) species.

IV. Update

As of June 20, 2000, EPA has still no action in response to a petition filed by environmental groups that asked the agency to rescind its regulatory exemption for ballast water discharges. However, the State of California has developed a “total maximum daily load” for exotic species under § 303(d) of the CWA that may have the effect of severely restricting ballast water discharges in that State.
Quantitative Biological Risk Assessment of the Ballast Water Vector: An Australian Approach

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Abstract: This paper reviews the need for ballast water risk assessment and describes three approaches: environmental matching that does not rely on species information, qualitative species-specific assessment, and quantitative species-specific assessment. The paper summarizes the progress to date on the ballast water risk assessment being developed by the Centre for Research on Introduced Marine Pests for the Australian Quarantine and Inspection Service. The risk assessment adopts a quantitative species-specific approach but also includes a simple hazard assessment based on environmental matching of the donor and recipient ports. In the first instance, the risk assessment will be applied to a target list of marine pests. Risk calculations are made via a series of modules that deal with discrete elements of the introduction cycle (donor port infection status, vessel infection scenarios, journey survival) up to and including survival in the recipient port. This endpoint has been selected to provide decision makers with a quantified measure of invasion risk with reasonable bounds of uncertainty. This is currently not possible for more complex endpoints such as the likelihood of establishment, or the expected economic and environmental costs of introduced species. The assessment maintains a precautionary approach in the face of uncertainty. This has been achieved by building different levels of assessment into some of the modules, allowing a progressively more accurate estimate of risk with additional data. If the requisite data are unavailable, the assessment defaults to the previous level of analysis or adopts a conservative stance.

Key words: introduced species, ballast water, quantitative risk assessment

INTRODUCTION

Ballast water is one of several ship-related vectors responsible for the modern dispersal of aquatic organisms around the world. At least 14 marine species are known "with reasonable certainty" to have been introduced into Australia through ballast water discharges (Jones 1991). Globally, over 104 marine and freshwater species are thought to have been introduced by this mechanism (Carlton 1985)—with significant environmental and economic costs (Carlton 1996). Recent evaluations of the rates of invasions into well-studied estuarine systems indicate that introductions are accelerating, possibly associated with the increase in ballast water movements around the globe since the late nineteenth century (Carlton 1996; Cohen and Carlton 1998; Hewitt et al. 1999). The scale and increasing rate of this problem, the seemingly irreversible nature of introductions, and the potentially devastating impact of exotic species (e.g. the zebra mussel, Dreissena polymorpha, invasion of the North American Great Lakes and the Atlantic comb-jelly, Mnemiopsis leidyi, invasion of the Black Sea), make ballast water introductions one of the most important environmental issues of the late twentieth century.

Australia has responded to the ballast water threat by establishing a National Ballast Water Management Strategy. This strategy seeks to "avoid the adverse economic and environmental impact of unwanted aquatic marine organisms by minimizing their risk of entry, establishment and spread ... whilst not unduly impeding trade" (Paterson 1995). The Australian Quarantine and Inspection Service (AQIS) is the lead governmental agency responsible for implementing this strategy. To do this, the Australian Ballast Water Management Advisory Council (ABWMAC) was established to aid AQIS in directing research and development. A risk-minimization approach, which is
founded upon a risk-assessment method capable of dealing with the complexities of the ballast water invasion cycle, has been adopted (Figure 1).

**Approaches to the Ballast Water Problem**

In 1991, the International Maritime Organization (IMO) introduced voluntary ballast management guidelines (Julian 1994), which recommend that all merchant vessels, *inter alia*, exchange their ballast water in mid-ocean, preferably in water depths of 2,000 m or more and beyond the 200-mi EEZ. Numerous nations are currently seeking a vehicle for international agreement, such as a new Annex to the International Convention for the Prevention of Pollution from Ships (MARPOL 73/78), to make these guidelines mandatory.

In the meantime, individual nations will continue to be threatened by international and domestic (or regional) vessels that do not undertake ballast water management (*e.g.*, exchange). Vessels may not exchange their ballast water because of several possibilities:

- safety concerns—exchanging ballast imposes bending moments and shear stresses on the vessel. At sea, the combination of bending moments and shear stresses imposed on the vessel by wave action and exchange activities can compromise the structural integrity of the vessel. Thus, even for largest vessels (>160,000 dwt), ballast exchange is not recommended if the significant wave height is greater than or equal to 6 m (AQIS 1993).
- the journey is too short—it takes time to safely exchange large volumes of ballast. For example, three days are needed to exchange the ballast water in all the tanks of the MV *Iron Whyalla* (141,475 dwt), using a three-volume flow through method (Rigby and Hallegraeff 1994).
- the vessel does not have a ballast water management plan approved by a certification society.
- the vessel chooses not to comply with the guidelines or regulations.

A nation can adopt one of three approaches to the problem of ballast water invasions: (1) it can do nothing, (2) it can decide that no introduction is acceptable ("zero risk"), or, (3) it can try to minimize the risk of ballast water introductions by tailoring management strategies to meet specified objectives ("risk management").

The first approach costs nothing, but introductions will continue unabated or even at an increasing rate. A proportion of these species will result in populations of pest species becoming established in the nation's ports and along its coasts. The economic and environmental costs can be high: the zebra mussel *Dreissena polymorpha*, for example, is estimated to cost US $300 million a year by obstructing cooling water intakes, and perhaps another US $200 million a year in nuisance costs (Weathers and Reeves 1996).

In the modern global economy, "zero risk"
quarantine policies are untenable. Australia also views such policies as undesirable and has formally rejected them (Department of Primary Industries and Energy 1988). Furthermore, short of banning all shipping trade, one would have to devise a management strategy that is acceptable to all stakeholders and 100% effective in order to implement such a policy. No such strategy currently exists. The risk management approach, therefore, is a compromise between doing nothing and the zero risk approach.
Ballast Water Risk Assessment

At least three different approaches to ballast water risk assessment have been proposed in Australia and elsewhere: (1) environmental matching, (2) qualitative, species-specific; and, (3) quantitative, species-specific.

Environmental Matching

Environmental-matching seeks to measure ballast water risk by evaluating the degree of environmental similarity between donor and recipient ports. This approach assumes that if a non-native species is repeatedly transferred to a foreign port, the likelihood that it will establish a viable long-term population is heavily dependent on the similarities between the biophysical conditions of the recipient port and donor ports (Hilliard and Raaymakers 1997). As a hazard analysis this is a very useful first step, but as a risk assessment it has flaws.

Ballast water management, via risk assessment or any other quarantine management system, acts only as a filter, not as a barrier (Carlton et al. 1995). Ballast water risk assessment based on environmental matching, however, is a far less effective filter for four reasons:

1. Environmental-match assessments will identify similarities or differences between port environments, but will not incorporate species-specific environmental tolerance ranges. Consequently, potentially hazardous routes that lie well within the tolerance range of an individual species, but are between two ports that differ in environmental parameters, will not be identified.

2. Temporal and spatial scales of the environmental information from the ports will define the similarity/dissimilarity match. For example, two ports may match at the start of a Northern Hemisphere spring/Southern Hemisphere autumn, but be otherwise unmatched. Alternately, the microenvironments in ports could confound match predictions. For example, the discharge into a port of power-station cooling water could raise the water temperature at a site, making it capable of supporting species that could not survive elsewhere in the port (Carlton 1992).

3. Carry-over of ballast water between ports can make an environmental match between the recipient port and a vessel’s last port of call (LPOC) immaterial to the true risks posed by the ballast water. In a study of American shipping patterns, Carlton et al. (1995) found that a vessel’s LPOC was a poor predictor of ballast source: 53% of all vessels (and 66% of container vessels) contained ballast water that did not originate from the LPOC. Furthermore, a small proportion of a vessel’s ballast is “unpumpable” because the pump pipe ends some distance from the bottom of the tank. For example, each vessel entering the Great Lakes, on average, carries 158 mt of residual unpumpable ballast (Locke et al. 1993). Thus, sediments at the bottom of a tank and some ballasted water are likely to be much older than the LPOC. Risk assessments based only on environmental similarity for all traded ports could become extremely conservative if they addressed this issue without estimates of how long organisms can survive in ballast water (see for example Murphy 1997; Gollasch et al. 1995; Wonham et al. 1996).

4. It is difficult to improve the risk assessment when a new introduction appears, for two reasons. If the origin of the species is unknown, then it is impossible to comment on the accuracy of the risk assessment in light of the new discovery. On the other hand, if the origin of the species is known, but the assessment predicted the source as unmatched, then the source must logically be reclassified as matched, which means that all vessels on that route must be regarded as hazardous. In effect, the assessment can only become increasingly conservative with increasing costs to the shipping industry (see Figure 2).

Despite these problems, the environmental-match approach has some merit. It can provide a useful measure of ballast water hazard, particularly if combined with a species-specific assessment. Together the two approaches can improve the risk assessment by helping to offset their individual limitations. The risk assessment developed by the Centre for Research on Introduced Marine Pests (CRIMP) advocates a combined approach (see below).

Qualitative, Species-Specific

A qualitative, species-specific approach requires the analyst to qualitatively score the probability of a species successfully passing through each step of the ballast water invasion cycle. For example, the pest risk assessment developed by the Animal and Plant Health Inspection Service (APHIS) of the United States Department of Agriculture (Orr 1993, 1995) scores a species’ presence in a vector, its entry
Figure 3. Species-specific risk assessments (I. Assessment) can be evaluated (II. Evaluation) and improved (III. Modification) when a new exotic species is discovered. If the species is not on the current target list, it should be added immediately and the assessment run to protect those areas that are not infected. If the species is already on the target list, the risk assessment is examined to see if the calculations can be improved in light of the new information.
potential, colonization potential, spread potential, economic impact potential, environmental impact, and perceived impact. It also allocates an uncertainty code to each of these scores to reflect the assessor’s certainty in this respect. New Zealand’s National Institute of Water and Atmospheric Research (Bradford-Grieve et al. 1998) advocate this assessment style for ballast water introductions.

In the short to medium term, this approach will provide only qualitative or mixed quantitative/qualitative outputs based on quantitative estimates of the early steps in the ballast water invasion cycle (e.g., presence and entry potential). Ecological science is many years away from being able to provide reliable quantitative measures of establishment (colonization potential) and impact (economic or environmental) for all species without extensive tests. Qualitative (or mixed output) risk assessments are well suited to examination by expert panels, who can discuss the evidence and reach a consensus on the risk, but are unsuited to rapid or real-time evaluations, because (1) the risk assessment process is difficult to automate, and (2) the overall vector risk (due to the presence of two or more species in a single vector) cannot be calculated.

The process is difficult to automate because there are (usually) too many risk permutations—overall risk estimates that are unique for a single species. For example, the APHIS pest risk assessment process scores seven steps in the invasion cycle as high, medium, or low, and allocates one of five uncertainty codes to each of these scores. The total number of risk permutations for any one species is therefore $(3 \times 5)^7 = 1.7 \times 10^8$—clearly a difficult procedure to automate.

If the probability of success at each step in the ballast water invasion cycle is independent (in a statistical sense) from species to species, then the overall vector risk for two or more species is the sum of the individual species risk—or more correctly, the multiple of the invasion probability complement. But how does one sum qualitative or mixed output expressions of species risk in a meaningful way? How many “negligible risks” sum to a “moderate risk”? This question simply cannot be answered in a qualitative fashion.

**Quantitative, Species-specific**

A more rigorous quantitative approach to the ballast water invasion cycle also requires a species-specific approach; however, extant risk assessment models do not adequately address the steps of the invasion cycle. Quantitative Risk Assessment (QRA) models, initially developed for the chemical and nuclear industries, however, provide a general approach to the development of a Quantitative Biological Risk Assessment for species introductions. The QRA model is broken into five steps: hazard identification (what are the undesired events), likelihood of the undesired events, consequences of these events, risk calculation, and significance and uncertainty analysis.

Hazard identification is the key component of any risk assessment process. Hazards that are not identified in the early stages of the assessment will not be taken into account at later stages, leading ultimately to an underestimate of risk. Numerous methods for identifying hazards are available, including the collation of expert “heuristics”, the use of fault tree analyses, and the use of hazard and operability analyses.

These methods are well suited to vector-based hazard identification; however, in order to develop a species-specific analysis it is assumed that criteria for identifying target species (the species hazard) are accepted and defined in advance. A well-established argument in quarantine risk assessment (see for example Orr 1993) is that mitigating measures developed for one species can be just as effective for other species with similar characteristics. The protection afforded by a species-specific assessment can therefore be improved by selecting target species that are representative of broad guilds or that are among the most robust relative to the determinants of ballast water transport: for example, species with wide environmental tolerances, pelagic larval, or resistant, resting life-stages. Ballast water strategies that are effective against these species will protect recipient ports from a much wider group of species.

The assessment procedure can be easily designed so that it is identical for any species and therefore any species can be assessed, assuming the data requirements are met. The important question remains, however, as to which species are pre-selected for assessment. Once an initial “target list” is developed, new or suspected marine pests discovered anywhere in the world could be added to this list. A quantitative species-specific risk assessment could then estimate the probability that this species would
also be introduced by ballast water once key biological information was collected.

If an existing target species is detected in a recipient port, but the site was not marked as at risk, then the assessment can be empirically modified to account for the error. Thus, the risk assessment can improve with time in an iterative learning fashion (see Figure 3). This might lead to more vessels being identified as hazardous but, unlike the environmental-matched approach, this outcome is not inevitable.

Calculating the likelihood and consequences of undesired events is the most difficult component of a quantitative ballast water risk assessment. The undesired events in question usually relate to the adverse economic and environmental impacts associated with the establishment of exotic species. To express these quantitatively, the analyst must model each step in the ballast water invasion cycle and ultimately link the probability that the species will be introduced, survive, and establish in the recipient region, with the consequences of this expressed in terms of, for example, loss of a commercial species or environmental impairment. As noted above, however, ecological science is many years away from being able to provide reliable quantitative measures of establishment and impact (economic or environmental) for invasive species without extensive tests. For example, toxic dinoflagellate introductions are estimated to have social costs (tourism, public health, and aquaculture—excluding broader ecosystem effects) in the region of $350–2000 million (AQIS 1994). The upper end of this range is almost certainly an underestimate because of environmental costs that are notoriously difficult to estimate.

Having said this, it would be unduly pessimistic to believe that qualitative risk estimates are the best that ballast water risk analysts can hope to achieve in the near term. The ballast water invasion cycle involves several steps—vector infection, survival, establishment and/or dispersal, and impacts. The uncertainty associated with each step increases from left to right, i.e., from infection to impacts. Quantitative probabilistic techniques become increasingly inappropriate as one moves from low to high uncertainty. It may not be necessary, however, to quantify all of the steps in the invasion sequence. For species which are a priori pests, with a well-documented impact history, quantified estimates of inoculation (i.e., all those steps up to and including survival in the recipient area), which are relatively certain, may be sufficient from a risk manager’s perspective.

The advantages of more certain, quantitative risk measures are enormous—risk estimates relative to acceptance criteria become meaningful, risk management strategies can be compared, and risk-benefit analyses conducted. To achieve this, however, an earlier endpoint in the ballast water invasion cycle (such as inoculation survival) must be used in the assessment. Note also that this remains a suitable platform to address the probability of establishment and subsequent economic/environmental impact when these components can be estimated with reasonable accuracy and scientific rigor.

The analyst can calculate the invasion risk associated with an individual species by multiplying the probability that the species successfully negotiates each step in the ballast water cycle by the attendant economic and environmental costs of establishment and spread. Currently, however, no quantitative species-specific approach has been developed that can readily be applied to the invasion process via ballast water, largely because of the difficulty of calculating the probability and cost of establishment.

Alternatively, if invasion risk is expressed purely in terms of inoculation, multiplying the probability that the species negotiates each step up to and including survival in the recipient region allows a much simpler risk calculation. The overall vector risk for one or more species is calculated by multiplying the complement of the risk of each individual species such that

\[
\text{Risk}_{\text{vector}} = 1 - \prod_{i=1}^{n} (1-p_i),
\]

where \(p_i\) is the invasion risk for species \(i\).

**The CRIMP Risk Assessment Framework**

The CRIMP risk assessment approaches the ballast water problem from the perspective of the invading species. It is therefore species-specific and will, in the first instance, be applied to a target list of selected species (Table 1) ratified by ABWMAC. These species have been designated as marine pests in their native or introduced ranges through a qualitative assessment by a panel of experts. The CRIMP assessment assumes that each of these species will represent a high risk if it were to be inoculated and survive in an Australian port.
Table 1. The current Australian Ballast Water Management Advisory Council target species list.

<table>
<thead>
<tr>
<th>Species</th>
<th>Common name</th>
<th>Life-stage category&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sabella (=Spirographis) spallanzanii</td>
<td>Sabellid fan worm, European fan worm</td>
<td>Larvae/gametes = meroplanktonic&lt;sup&gt;b&lt;/sup&gt;; juvenile/adult = benthic (hard); possibly tycho planktonic or floating detachable</td>
</tr>
<tr>
<td>Carcinus maenas</td>
<td>European shore crab, green crab, N. Atlantic edible shore crab</td>
<td>Larvae/gametes = meroplanktonic&lt;sup&gt;b&lt;/sup&gt;; juvenile/adults = benthic (hard and soft); possibly tycho planktonic as juveniles</td>
</tr>
<tr>
<td>Asterias amurensis</td>
<td>N. Pacific seastar, Japanese seastar</td>
<td>Larvae/gametes = meroplanktonic&lt;sup&gt;b&lt;/sup&gt;; juvenile/adults = benthic (hard and soft); possibly tycho planktonic as juveniles</td>
</tr>
<tr>
<td>Undaria pinnatifida</td>
<td>wakame</td>
<td>Gametophytes/sporophytes = benthic (primarily hard, some soft, associated with seagrasses and shells) and tycho planktonic; some indication of formation gametophyte ball, which may become suspended in water column; possibly floating detachable due to settlement of other algae</td>
</tr>
<tr>
<td>Alexandrium catenella</td>
<td>Toxic cyst-forming dinoflagellates</td>
<td>Adults = holoplanktonic&lt;sup&gt;b&lt;/sup&gt;; cysts = tycho planktonic</td>
</tr>
<tr>
<td>A. minutum</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A. tamarense</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gymnodinium catenatum</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Musculista senhousia</td>
<td>Asian mussel, Bag or Senhouse’s mussel</td>
<td>Larvae/gametes = meroplanktonic&lt;sup&gt;b&lt;/sup&gt;; juvenile/adult = benthic (hard and soft); possibly floating detachable and tycho planktonic due to settlement on seagrass and algae.</td>
</tr>
<tr>
<td>Corbula gibba</td>
<td></td>
<td>Larvae/gametes = meroplanktonic&lt;sup&gt;b&lt;/sup&gt;; juvenile/adult = benthic (soft and some nesting); possibly tycho planktonic</td>
</tr>
<tr>
<td>Crassostrea gigas</td>
<td>Japanese oyster, Pacific (king or rock) oyster</td>
<td>Larvae/gametes = meroplanktonic&lt;sup&gt;b&lt;/sup&gt;; juvenile/adults = benthic (primarily hard but can settle on soft to form oyster beds); possibly tycho planktonic as juveniles due to settlement on seagrass and algae.</td>
</tr>
<tr>
<td>Potamocorbula amurensis</td>
<td>Chinese clam, Asian bivalve</td>
<td>Larvae/gametes = meroplanktonic&lt;sup&gt;b&lt;/sup&gt;; juvenile/adults = benthic (soft and some nesting); possibly tycho planktonic</td>
</tr>
<tr>
<td>Mnemiopsis leidyi&lt;sup&gt;c&lt;/sup&gt;</td>
<td>Comb jelly</td>
<td>Adults/larvae = holoplanktonic&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<sup>a</sup>after Carlton et al. (1995), <sup>b</sup>possible vertical migrators, <sup>c</sup>not currently known from Australian waters

The risk assessment aims to provide a predictive, quantitative estimate of ballast water risk to:
- screen and prioritize vessels for sampling (on arrival) by field officers;
- allow a risk-benefit analysis for different strategies of ballast water management;
- encourage the shipping industry to change its operations in order to minimize the risk of introducing (or spreading) exotic marine species in Australian waters, while simultaneously decreasing its management costs; and
- compare the threat from ballast water to other vectors.

**Endpoint Selection and Ballast Water Risk**

The purpose of a predictive risk assessment is to prevent or minimize harm, which is expressed through the assessment endpoint. Appropriate endpoint selection is critical to the success of any ecological risk assessment (Suter 1993). The endpoint selected for the CRIMP ballast water risk assessment is the survival of a non-native organism in the recipient port at the time of inoculation.

It has been suggested that limiting the risk assessment to a survival endpoint can be justified only when the probabilities and consequences of establishment are indistinguishable between targeted species (Bradford-Grieve et al. 1998). This is not implied; rather, the survival endpoint was chosen for three reasons:
- it is appropriate for a quarantine, barrier-control, risk assessment;
- it provides a suitable basis for risk-benefit analysis for species that are a priori classified as marine
Table 2. The universal set in a donor port can be characterized according to the habitat and behavior of the species concerned.

<table>
<thead>
<tr>
<th>Category</th>
<th>Member examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHYTOPLANKTON: diatoms, dinoflagellates, blue-green algae, nanoplankton, autotrophic picoplankton, and other groups. ZOOPLANKTON: comb jellies, jellyfish, hydrozoans (siphonophores), polychaete worms, rotifers, gastrotrichs, planktonic gastropods (snails: the pteropods and heteropods), copepods, hyperiid amphipods, isopods, mysids, ostracods, cladocerans, pelagic shrimps, krill (euphausiids), arrow worms (chaetognaths), pelagic tunicates (including salps, doliolids and larvaceans). FISH</td>
<td>Larvae and juveniles of the by-the-wind-sailor siphonophore Velella, the blue button Porpita, nauplii and cyprids of the barnacle Lepas, and the sea strider Helobates</td>
</tr>
<tr>
<td>MEROPLANKTON: Temporary plankton — organisms that spend a portion (usually the shorter!) of their life cycle in the plankton. ZOOPLANKTON: the larvae of many benthic invertebrates including sponges, sea anemones, corals, hydroids, molluscs (snails including sea slugs or nudibranchs), chitons, mussels, clams, oysters, scallops, crustaceans (barnacles, shrimp, lobsters, crabs, hermit crabs), nemertean (ribbon worms), sipunculans, polychaete worms, bryozoa, phoronids, echinoderms (seastars, brittle stars, sea urchins, sea cucumbers), hemichordates, tunicates (sea squirts) FISH: eggs and larvae</td>
<td>These organisms include a variety of small crustaceans (including gammarid amphipods, isopods, mysids, cumaceans, crangonid and other shrimp, and benthic harpacticoide copepods), some fish species, and polychaete worms. Other examples are the wood-boring gribble Limnoria, a tiny isopod crustacean that migrates at night by swimming between wood habitats.</td>
</tr>
<tr>
<td>MIGRATORY organisms, including DEMERSAL organisms that migrate vertically towards the surface</td>
<td>Foraminifers, flatworms, polychaetes, crustaceans (copepods, amphipods, isopods and tanaids), hydroids, benthic copepods, insect larvae and adults, mites, nematodes, leeches, oligochaete worms</td>
</tr>
<tr>
<td>TYCHOPLANKTON (organisms that can be removed from their previous habitat by tidal currents, waves, and ship’s propellers, etc., including benthic organisms that could be brought into the vessel with bottom sediment)</td>
<td>Seaweeds (algae), seagrasses (eelgrass, Sargassum, turtle grass), marsh plants, spirobid tubeworms, bryozoans, sea squirts, sponges, molluscs, crustaceans</td>
</tr>
<tr>
<td>FLOWING DETACHED biota including EPiphytic organisms on the blades of floating plants</td>
<td>Marine diseases, pathogens, and parasites, including mariculture and aquaculture diseases</td>
</tr>
</tbody>
</table>

pests, or potential pests; and
- it provides a clear (and verifiable) risk measure that avoids the more complex expression of the likelihood of establishment and of adverse environmental or economic impact.

By limiting the endpoint to survival, the CRIMP assessment is able to provide decision-makers with a quantified measure of invasion risk with reasonable bounds of uncertainty. Furthermore, with an inoculation survival endpoint, ballast water risk on a per vessel/per voyage basis can be calculated with the following elements for each target species:
- the probability \( p(o) \) that each port from which a vessel derives ballast (donor port) is contaminated with the target species;
- the probability \( p(o) \) that the vessel is subsequently infected with any of the life-stages of the target species;
- the probability \( p(\psi) \) that the inoculum survives the journey; and
- the probability \( p(u) \) that the life-stage at the end of the journey will survive if discharged into the recipient (Australian) port.

Ballast water risk can be calculated by assigning probability to each of these steps, such that:

\[
\text{Risk}_{\text{species}} = p(o) \cdot p(\psi) \cdot p(u) \quad [2]
\]

**Hazard Identification—Vessel Infection Scenarios**

Two hazard-identification procedures are used in the CRIMP risk assessment framework:
1. Fault-tree analysis to identify vessel-infection scenarios—the circumstances in which a vessel’s ballast water becomes contaminated with target pests; and

2. Hazard and Operability (HAZOP) analysis to test for deviations from the “normal” environmental conditions in recipient ports and port-based activities that might confound the predictive algorithms in the assessment (refer to Hayes and Hewitt 2000 for further details).

Fault trees are hazard analysis tools that are used in quantitative risk assessment to identify the chain of events leading to a hazardous occurrence (Kletz 1986). They identify the logical combinations of events that are precursors of hazardous situations and, importantly, highlight the ways in which the event chain can be broken. If probability or frequency data can be generated for the basic events at the ends of each branch, then Boolean algebra can be used to estimate the overall frequency of the hazardous occurrence. This is not, however, the objective of the fault trees developed for this framework. Rather, their purpose is to identify all the potential vessel-infection scenarios in contaminated donor ports (for example see Figure 4).

The fault tree analysis provides a rigorous, explicit, and systematic description of the taxonomic hazard in donor ports and identifies a number of subtle (and less tractable) hazards within the ballast water introduction cycle. The “taxonomic hazard” is the set of species that can be introduced via ballast water. The universal set is defined as the complete floral and faunal assemblage in the donor port. This set can be categorized according to the life-stage characteristics of the species concerned (Table 2).

The fault-tree analysis helped define 10 vessel-
Table 3. Vessel-infection scenarios identified in the CRIMP risk assessment by a fault tree analysis.

<table>
<thead>
<tr>
<th>Water column</th>
<th>Planktonic</th>
<th>Tycho-planktonic</th>
<th>Neuston</th>
<th>Vertical</th>
<th>Floating</th>
<th>Detached</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Sof.

Hard

Epiphyte

Table 4. Hazard and risk assessment levels in the CRIMP risk assessment framework.

<table>
<thead>
<tr>
<th>Level</th>
<th>Assessment (cumulative)</th>
<th>Principal data needs (additional)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Tests for donor-port infection and species tolerance of recipient port. Provides qualitative hazard rank.</td>
<td>Ballast source, donor port/bio-region infection status, recipient port temp/salinity maxima, species temp/salinity tolerance.</td>
</tr>
<tr>
<td>1</td>
<td>Tests life-stage entry into ballast tank, journey duration against life-stage duration, and simple entrainment analysis. Provides qualitative hazard rank.</td>
<td>Life-stage size and duration maxima, ballast sieve size, date since sieve was last serviced, life-stage habitat and characteristics, ballast event date and time.</td>
</tr>
<tr>
<td>2</td>
<td>Models journey survival. Provides quantitative estimate of risk (assuming probability of survival in recipient port = 1).</td>
<td>Journey survival model and requisite parameters, ballast method.</td>
</tr>
<tr>
<td>3</td>
<td>Models life-stage survival in recipient port. Includes environmental subunit definition (recipient port) and environmental HAZOPE analysis. Provides quantitative estimate of risk.</td>
<td>Recipient berth details, temperature and salinity extreme values, density estimate of extremes, EV distribution and requisite parameters.</td>
</tr>
</tbody>
</table>

infection scenarios (Table 3) based on the life-stage characteristics and the life-stage habitat—soft substrate, hard substrate, water column, or epiphyte. The likelihood of vessels becoming infected in each of these scenarios, for each life stage, will be modeled within the framework (see Module III below). The large number of infection scenarios underlines the complexity of the ballast water problem, and emphasizes the importance of using systematic hazard identification tools. Indeed, the success of the fault trees in this context suggests that they could be usefully employed in other complex biological systems.

The fault-tree analysis also helped to identify the roles of less obvious ballast water hazards, namely:

- ballast tank populations—species that reside and reproduce within the ballast tank. This could be a very hazardous scenario if “fresh” (i.e., not subject to the rigors of the journey) inoculations of larvae occur when the vessel de-ballasts.
- ballast water carry-over caused by multiple ballast sources in tank, or because of unpumpable ballast.
- crevicolous species—species which actively seek crevices and holes. The risk assessment assumes that entrainment into the ballast tank is essentially a passive process, and the infection probability is estimated accordingly. However, the probability of infection could be much higher for species that seek sea chests for shelter.
- third-party infection scenarios—the infection of vessels in ports that are themselves uncontaminated, but may have infected vessels in port that are discharging contaminated ballast water next to vessels which are taking on ballast water. This scenario is unlikely but not impossible.

With a species-specific approach, all of these hazards are amenable to analysis. For example, if the journey duration exceeds the duration of the larval stages of a fouling species, then these vessels can be flagged as potentially having juveniles settled on the inside of their ballast tanks. Hazards associated with unpumpable ballast can be assessed in relation to the age of the water and the likelihood of the species surviving in the ballast tank. Finally, the probability of vessel infection can be increased to allow for the behavior of crevicolous species whenever they are present in a donor port. Third-party infection scenarios, however, could probably be addressed only by a very sophisticated analysis (such as that envisaged at level 5 of the risk assessment framework—see below). For this reason, the probability of a vessel becoming infected is set at an arbitrary minimum value (0.05).

Levels of Hazard and Risk Assessment

The CRIMP risk assessment is designed to provide an increasingly accurate estimate of risk as more information is made available to the analysis. This has been achieved by writing six levels or tiers of analysis (0–5) into the framework. In the first instance (level 0), two qualitative hazard assessments are made based on simple environmental comparisons (between donor and recipient ports) and the
known distribution of target pests. The data requirements of this level are minimal: donor-port infection status, monthly temperature and salinity extremes of the donor and recipient ports, and the temperature and salinity tolerances of the target pest.

Table 4 summarizes the additional analyses and data requirements of the framework up to and including a level 3 analysis. At level 3, the assessment tests infection scenarios, models the survival of a pest during the vessel's journey, and estimates the probability of a pest surviving in the recipient port. Data requirements are increased, but the estimate of ballast water risk becomes more accurate. Additional levels of analysis (levels 4 and 5) are envisaged to include vessel-specific zooplankton suspension analysis and port-circulation models (for further details see Hayes and Hewitt 1998, 2000).

In the absence of the requisite data, the assessment defaults to the highest level of analysis for which data are available. For example, the probability of survival in the recipient port is assumed to be 1.0 in a level 2 analysis. Similarly, a level 2 analysis stops and defaults to level 1 if there are insufficient data to run a model of journey survival. This ensures that the assessment maintains a conservative stance in the face of uncertainty, while also providing tangible benefits (in terms of risk reduction) for additional data costs.

**The Risk Assessment Modules**

The risk assessment framework is made up of five modules. The first (Module 0) collects data from the vessel on the origin of its ballast water and associated details. The remaining modules mimic the invasion process by dealing with individual steps in the ballast water introduction cycle up to the point of survival in the recipient port. The risk assessment modules and the role they play in the overall framework are illustrated in Figure 5.

**Module 0—Data Collection**

Module 0 collects information on the assessment date (expected arrival of the vessel in the recipient port), the name of the recipient port, the berth, the vessel's name, IMO number, and details of the ballast on board.

Ballast information is collected on a tank-by-tank basis, including date, volume, start/end time, method, and the vessel's draft at the start and end of ballast transfer. The module currently allows for three different ballast sources for each tank, in order to assess the risks of ballast water carry-over and the mixing of ballast water in and between tanks, but it is desirable to take into account all ballast origins for each tank.

**Module I—Port Infection Status**

The objective of Module I is to determine the probability of port infection. If a survey of a donor port detects a target species, then the probability of infection \( p(0) \) is equal to 1.0. If the survey did not detect a target species, then the probability of infection is the product of the probability of a type II error (the species was present but not detected by the survey) and the probability that species can actually survive in the port. The probability of a type II error can be determined using geometric probability arguments and line intersect and transect sampling theory (see Hayes and Hewitt 2000 for details) and is in part alleviated by using a standardized sampling design and methodology (Hewitt and Martin 1996).

Ultimately, the probability of port infection will also be linked to the time elapsed since the last survey.

If the port concerned has not been surveyed, then its infection status is inferred from that of the bioregion in which the port is located. A database detailing the bioregions of the world, their infection status, and the ports they encompass has been developed by CRIMP. This is largely based on the bioregional classification of Hayden et al. (1984) as adopted by the International Union for the Conservation of Nature (Kelleher et al. 1995), ports information from the Fairplay Ports of the World Guide (Fairplay 1998), and the published distributions of species on the target list.

**Module II—Port Environment**

Module II characterizes the port environment. It is used at level 0 to determine whether the species can tolerate the temperature and salinity maxima and minima of the recipient port. In level 3, the module uses empirical density or kernel density estimates (Silverman 1986) of daily temperature and salinity extremes or, given enough data, extreme-value theory, to estimate the probability \( p(v) \) that the target species will survive in the recipient port. The same techniques are used to calculate the probability that the target species can survive in the donor port, in order to determine the probability of infection (see above).

From level 3 onwards, the geographical unit of
Figure 5. The CRIMP ballast water risk assessment framework illustrating the risk assessment modules used to collect data from the vessel and to calculate ballast water risk.
assessment is based on environmental subunits, to which all berths in the recipient port are allocated. The subunits are analogous to the delineation of eco-regions based largely on climatic similarity (Bailey 1983). Relatively small ports may comprise just one environmental subunit, while larger ports may comprise two or more subunits. In addition, ports with unique artificial environmental areas such as heated outflows will be identified. This approach emphasizes that the management boundaries of a port may not be the most appropriate for risk assessment purposes. At levels 4 and 5, module II may also be used to extend the survival analysis to include a wider set of environmental parameters such as dissolved oxygen, pH, or nutrients, depending on the availability of data.

Module III—Vessel-Infection Scenarios

Module III models the vessel-infection scenarios for life stages that are small enough to enter the ballast tank (as determined by the ballast sieve diameter, maximum life-stage size, and some allowance for corrosion of the sieve). For the life-stages of most species, vessel-infection scenarios will be mutually exclusive. The overall probability of vessel infection is defined as:

\[
p(\phi) = 1 - \prod_{r=1}^{m} \prod_{i=1}^{n} [1 - p(\phi_{ri})]
\]

for the life-stages \((r = 1 \text{ to } m)\) of particular target-species, under infection scenarios \((i = 1 \text{ to } n)\).

Infection analysis is not conducted at level 0; the probability of vessel infection is simply assumed to be 1.0. At level 1, the vessel-infection analysis is relatively simple. Water-column-sourced planktonic and neustonic infections occur \((p(\phi_{ri}) = 1.00)\) whenever life stages of the species are expected to be in the water column. Otherwise the life-stage(s) are assumed to be unavailable to the vessel \((p(\phi_{ri}) = 0.05)\), allowing for the unquantified third-party risk.

* Asterias amurensis*, for example has five life history stages: egg/gastrula, bipinnaria, brachiofario, juvenile, and adult. Vessel-infection scenarios for each life stage are mutually exclusive. The larval life stages (egg/gastrula, bipinnaria and brachiofario) can cause water-column sourced, planktonic infections (Table 3). Like many echinoderms, the larvae spend a relatively long time in the plankton. In the Derwent estuary, larvae are likely to be in the water column from July to January (Byrne et al. 1997; CSIRO unpublished data). In a level 1 analysis, vessels ballasting in Hobart during this period would be classified as infected \((p(\phi_{i1}) = 1.0); \text{ where } i = 1 \text{ [water-column/plankton]}, \text{ and } r = 1 \text{ to } 3 \text{ [three larval stages]})

* Gymnodinium catenatum* has two life history stages: vegetative cells and cysts. The vegetative cells can cause water-column-sourced planktonic infections whenever they are present in the water column, particularly during bloom events. The cysts, however, are associated with two vessel-infection scenarios that are not mutually exclusive: cyst production during blooms can lead to water-column sourced planktonic infections, and resuspension of cysts from contaminated sediments can lead to soft-substrate sourced tychoplankton infections (Hallegraeff 1998).

In a level 1 analysis, vessels ballasting in deep ports, outside of a bloom, would be classified as infected with vegetative cells \((p(\phi_{i2}) = 1.0); \text{ where } i = 1 \text{ [water-column/plankton]} \text{ and } r = 1 \text{ [vegetative cells]})\). In shallow ports where sediment resuspension occurs due to natural processes, vessel-berthing activity, or other port-based activity during a bloom, vessels would be classified as infected \((p(\phi_{i2}) = 1.0); \text{ through three scenarios: } i = 1, 2 \text{ [water-column/plankton and soft-sediment/tychoplankton]}, \text{ for } r = 2 \text{ [cysts]}; \text{ and } i = 1 \text{ [water-column/plankton]}, \text{ for } r = 1 \text{ [vegetative cells]})\). More sophisticated levels of analysis are envisaged at level 4, based on the Rouse equation and propeller-wash models, together with an analysis of the ballast-withdrawal envelope (see Hunter 1997; Hayes and Hewitt 2000). This analysis, however, requires extensive data input, including information on third-party vessel activity in the donor port. So while most of the theory for these models is well developed, they have not been incorporated into the lower levels of the framework because they are data intensive.

Module IV—Journey Survival

The objective of Module IV is to determine the probability that the life stage(s) entrained into the ballast tank survive the journey. At level 1, a simple competency analysis compares the journey's duration with the minimum time to settlement for those life stages that are small enough to enter the ballast tank. If the journey's duration exceeds this period, then a warning is issued about the potential for ballast-tank populations.

At level 2, module IV models journey survival based on journey duration, an appropriate statistical
model and its associated parameters (for example see Hayes 1998). Higher levels of analysis may also incorporate the effects of en-route ballast management strategies (e.g., open-ocean ballast water exchange, heat treatment) and pump versus gravity ballasting in order to reflect the expected influence of the ballast pump on the species surviving the journey (see for example Gollasch et al. 1995; Murphy 1997 and Hallegraeff 1998).

**Future Research Directions**

The framework provides a blueprint for ballast water risk assessment. In the first instance, the risk/hazard assessments may be quite crude. The models and risk algorithms used in the framework will probably change as it develops and additional data are collected. The multi-level, modular approach, however, will remain, and with time the framework will provide more accurate estimates of risk. The future development of the framework is expected to include:

1. increasing the knowledge base by gathering port environmental data (international and national) and biological data on the behavior and tolerance of target species
2. assessing port-infection status relative to the probability of a type II error during a survey, date of the last survey, and the availability of pest-monitoring strategies
3. developing journey-survival models for relevant life stages of species on the targeted list
4. modeling propeller wash and sediment resuspension. Initial studies in this area (Murphy 1998) indicate that the theory of propeller wash and sediment re-suspension/settlement is sufficiently advanced to implement vessel/berth specific models of tychoplankton infection from soft sediments. This is an important infection scenario for the cysts of dinoflagellate species outside their relatively short bloom windows (Hallegraeff and Bolch 1992)
5. examining the feasibility of using port circulation models in conjunction with models of the ballast withdrawal envelope to determine the probability of vessel infection and the size of the inoculum
6. developing ground-truthing procedures to test the predictions of the risk assessment and provide additional data to continually improve the assessment algorithms. These procedures could be developed in conjunction with Bayesian inference techniques to allow rapid updates of risk estimates, in accordance with the iterative improvement of quantitative risk assessment.

**Discussion**

Quantitative ballast water risk assessment, as with any other management strategy, will not eliminate ballast-mediated invasions. It does, however, offer at least two important advantages over our current state of uncertainty:

- it will help clarify the importance of ballast water in relation to other transport vectors; and
- it will provide a means to test the cost-effectiveness of ballast management strategies.

Currently, it is very difficult to investigate the cost-effectiveness of ballast management strategies. The economic costs are relatively easy to quantify: for example, the operating costs of ballast water exchange are estimated to be US $0.014–0.045 per mt ballast (Rigby and Taylor this volume), so the total operating cost of mandatory ballast water exchange, for foreign shipping bound for the United States would therefore lie in the region of US $112–362 million per annum (using Carlton’s 1995 discharge estimate and assuming 100% compliance).

By contrast, the benefits of ballast water management are probable and extremely difficult to quantify. For example, ballast water exchange is thought to eliminate 67-86% of the zooplankton in a tank (Locke et al. 1993), but probably fewer of the organisms resident in ballast tank sediments, and may under some circumstances exacerbate the problem (Hay et al. 1997; Hallegraeff pers. comm.).

The benefits of exchange could be considerable—at least US 500 million per annum using Weathers and Reeves’ (1996) estimate—assuming it could prevent the introduction of a species as noxious as the zebra mussel and that ballast was the responsible invasion vector in the first instance. Without a quantified risk assessment, however, it is impossible to quantify the importance of ballast water as a vector, to value the expected benefits of exchange, or to identify the circumstances when other management options might be more appropriate.

It seems very unlikely that any single management strategy will be the most cost-effective for all vessels on all domestic and international routes. A quantified ballast water risk assessment, using target or representative species or both, will allow managers and the shipping industry to maximize the impacts...
of research and management activity. Ultimately, the assessment is expected to contribute to a wider Integrated Ballast Management strategy similar to that envisaged by Carlton et al. (1995), but allowing for a variety of management options, including instances where vessels cannot exchange their ballast water because the journey is too short or the weather is too bad. In this way, the risk assessment would allow flexibility in our response to the vessel, species, and site-specific factors that underlie ballast water invasions.

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LITERATURE CITED


Carlton, J.T., D.M. Reid, and H. van Leeuwen. 1995. The Role of Shipping in the Introduction of Non-indigenous Aquatic Organisms to the Coastal Waters of the United States (Other Than the Great Lakes) and an Analysis of Control Options. Report No. CG-D-11-95, National Technical Information Service, Springfield, Virginia.


Murphy, K.R. 1998. Predicting Currents Due to Shipping Operations for Ballast Water Risk Assessment. B.Eng. (Honours), Faculty of Engineering and Mathematical Sciences, University of Western Australia, Perth.


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