

## Failure of the Public Health Testing Program for Ballast Water Treatment Systems

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### Abstract

Since 2004, an international testing program has certified 53 shipboard treatment systems as meeting ballast water discharge standards, including limits on certain microbes to prevent the spread of human pathogens. We determined how frequently certification tests failed a minimum requirement for a meaningful evaluation, that the concentration of microbes in the untreated (control) discharge must exceed the regulatory limit for treated discharges. In 95% of cases where the result was accepted as evidence that the treatment system reduced microbes to below the regulatory limit, the discharge met the limit even without treatment. This shows that the certification program for ballast water treatment systems is dysfunctional in protecting human health. In nearly all cases, the treatment systems would have equally well "passed" these tests even if they had never been turned on. Protocols must require minimum concentrations of targeted microbes in test waters, reflecting the upper range of concentrations in waters where ships operate.

### 1. Introduction

Ships' ballast water discharges can introduce bacterial pathogens and diseases into novel regions of the world (McCarthy and Khambaty, 1994; Dobbs and Rogerson, 2005; Cohen et al., 2012; Rivera et al., 2013). For example, there is strong evidence that ballast water has introduced pandemic strains of both *Vibrio cholerae* and *V. parahaemolyticus* into new coastal regions (McCarthy and Khambaty, 1994; Qulici et al., 2005; Cabañillas-Beltran et al., 2006; Nair et al., 2007; Ansedo-Bermejo et al., 2010; Rivera et al., 2013), and scientists at the Centers for Disease Control recently warned of the need to treat ballast water to prevent the spread of cholera from Haiti (Cohen et al., 2012). Several researchers (National Research Council, 1992; Epstein et al., 1993; McCarthy and Khambaty, 1994) and the Pan American Health Organization (Anderson, 1991) concluded that the 1991 cholera epidemic in South America, which resulted in over one million cases of cholera and 10,000 deaths (Tauxe et al., 1995), likely arrived from Asia in ballast water, though others have questioned this pathway (Martinez-Urtaza et al., 2008; Lam et

al., 2010). At least 38 species of pathogenic bacteria and a high incidence of antibiotic resistance have been detected in ballast tanks (Dobbs and Rogerson, 2005; Altug et al., 2012; ; Buzoleva et al., 2012; Dobbs et al., 2013).

The global health risk posed by ballast water discharges was recognized 40 years ago, when the UN's International Conference on Marine Pollution asked the World Health Organization to initiate research on "the role of ballast water as a medium for the spreading of epidemic disease bacteria" (International Conference on Marine Pollution, 1973). The risks were noted again in 1991 when the UN's International Maritime Organization (IMO) adopted ballast water guidelines recognizing that "the discharge of ballast water and sediment has led to unplanned and unwanted introductions of...pathogens that are known to have caused injury to public health" and "the introduction of diseases may...arise as a result of...waters being inoculated with large quantities of ballast water containing viruses or bacteria, thereby posing health threats to indigenous human, animal and plant life" (IMO, 1991).

In 2004 the IMO drafted an international treaty, the International Convention for the Control and Management of Ships' Ballast Water and Sediments (hereafter "IMO Convention"), which would limit the concentrations of five organism groups in ballast water discharges (Table 1), including three bacteria (referred to by IMO as "indicator microbes") whose limits are intended to protect human health. The limits on *Escherichia coli* and intestinal enterococci are based on the use of these microbes as indicators of human fecal contamination resulting from inadequately treated or untreated sewage discharges, and are identical to European Union water quality parameters for coastal bathing waters (Council of European Community, 2006). The limit on toxigenic *Vibrio cholerae*, which refers to the toxigenic strains of *V. cholerae* serogroups O1 and O139 responsible for the 7th and 8th cholera pandemics, was included at Brazil's request after the 7th pandemic strain erupted in South America and was found in the ballast tanks of ships arriving in Brazilian ports (IMO, 2003). These same ballast water discharge limits were later included in US Coast Guard regulations adopted under the National Invasive Species Act in 2012 (US Coast Guard, 2012) and in permit requirements issued by the US Environmental Protection Agency under the Clean Water Act in 2013 (US EPA, 2013).

**Table 1. Concentration limits for living organisms in ballast water discharges set by the IMO Convention, the US Coast Guard, and the US Environmental Protection Agency\***

Organism group	Concentration limit
Organisms >50 µm in minimum dimension	10/m <sup>3</sup>
Organisms 10–50 µm in minimum dimension	10/mL
Indicator microbes:	
<i>Escherichia coli</i>	250 cfu/100 mL
Intestinal enterococci	100 cfu/100 mL
Toxigenic <i>Vibrio cholerae</i> (O1 and O139)†	1 cfu/100 mL

\* IMO, International Maritime Organization; cfu, colony-forming units.

† The IMO Convention also contains a limit of 1 cfu of toxigenic *V. cholerae* (O1 and O139) per 1 gram (wet weight) of zooplankton samples.

Implementation of the IMO Convention (which may be close to ratification) is effected in part through a program initiated in 2004 that tests and certifies shipboard ballast water treatment systems as being capable of meeting the discharge limits, referred to as type approval. Protocols for conducting type approval tests both in land-based testing facilities and in shipboard installations are described in an annex to the Convention (IMO, 2005). Although it is possible that type approving agencies may sometimes consider other performance data, these test results

are the only performance data mentioned or required by the IMO guidelines on granting type approval (IMO, 2005), and the only data cited in the IMO documents reporting type approvals. These tests are thus central to the type approval process. Similar protocols for the tests needed for US type approval were developed by the US Coast Guard and the US Environmental Protection Agency (US Coast Guard, 2012; Lemieux et al., 2010). Under the Alternate Management Systems (AMS) program, the Coast Guard can also allow temporary use (for up to 5 years) of treatment systems that have been type approved by an IMO member country (US Coast Guard, 2012).

Testing based on IMO protocols began 10 years ago, and testing based on the draft or final US protocols began four years ago. Although disclosure of the test results used to assess treatment system performance and grant type approval is not required, some system manufacturers have voluntarily released test reports or summaries of the results; others have chosen not to do so. However, there is now sufficient data available to support a review of the test program. Here we evaluate whether the tests are effective in verifying that approved treatment systems are capable of meeting the international and US ballast water discharge standards for microbes.

## 2. Methods

In both the IMO and US test protocols, the water used to test the treatment system is split into treatment and control streams. The control stream is passed into either an actual ballast tank (in shipboard tests) or a large tank intended to simulate a ballast tank (in land-based tests), where it is held for a period of time (variable in shipboard tests; at least 5 days (IMO) or 1 day (US) in land-based tests) before being discharged (IMO, 2005; Lemieux et al., 2010). The procedure for the treatment stream is identical except that the water treatment being tested is applied at the appropriate stage or stages, either on intake before entering the tank, while the water is in the tank, or during discharge from the tank. The concentrations of organisms targeted by the regulations are measured at various points, and a treatment system is determined to have passed the test if the concentrations in the treated discharge do not exceed the regulatory limits. To date, 53 shipboard treatment systems have been granted type approval by one or more IMO member countries, and 45 of these have been accepted as AMS by the US Coast Guard.

We assembled and analyzed all available data on the concentrations of the three regulated microbes in intake, treated discharge, and untreated (control) discharge samples in tests of ballast water treatment systems that followed the IMO or US protocols (Table S1 in Supplementary Material). We assembled these data from publicly released reports on land-based or shipboard trials conducted by test facilities and researchers (35 reports), supplemented by summary results included in IMO documents or type approval certificates (20 documents) or released by equipment manufacturers or test facilities (4 reports), that were available through October 1, 2013.

Since a treatment system passes these tests if the organism concentrations in the treated discharges do not exceed the regulatory discharge limits, the concentrations in the untreated (control) discharge water must, at a minimum, exceed the discharge limits if the test results are to provide information about the effectiveness of the treatment systems. We checked the assembled data against the regulatory discharge limits to determine what portion of the tests conducted under the IMO or US protocols satisfied that requirement (see Detailed Methods in the Supplementary Material). We calculated these proportions for all treatment systems, for all type-

approved treatment systems and for all AMS for which there are publicly released data on untreated discharge concentrations. For trials where untreated discharge concentrations are not available, we checked whether the intake concentrations exceeded the regulatory discharge limits.

### 3. Results

We obtained data on 390 land-based or shipboard trials conducted between 2004 and 2013 on 38 different treatment systems, including 31 of the 53 treatment systems granted type approval under the IMO Convention and 28 of the 45 treatment systems accepted as AMS by the US Coast Guard. In trials where untreated discharge concentrations were reported, they were less than the regulatory discharge limit for *E. coli* 97% of the time (n=332 trials, 35 treatment systems), below the limit for intestinal enterococci 91% of the time (n=315 trials, 35 treatment systems), and below the limit for toxigenic *V. cholerae* 100% of the time (n=176 trials, 26 treatment systems) (Table 2: All treatment systems; Figure 1). Untreated discharge concentrations for total *V. cholerae* were below the regulatory discharge limit for toxigenic *V. cholerae* 95% of the time (n=152 trials) (Table S1 in Supplementary Material). About half of the *E. coli* and intestinal enterococci untreated discharge concentrations, and all of the toxigenic *V. cholerae* untreated discharge concentrations, were below detection limits (Table 2: All treatment systems; Figure 1). In all, out of 823 measurements of regulated microbes in untreated discharges, the concentrations were below the discharge limits 95% of the time, and below detection limits 62% of the time (Table 2: All treatment systems).

**Table 2. Concentrations of regulated microbes in the untreated (control) discharge in trials conducted according to IMO or US protocols\***

Organism group	n <sub>measurements</sub>	n <sub>treatment systems</sub>	< Detection limit†	≥ Detection limit and < Regulatory limit†	≥ Regulatory limit†
<b>All treatment systems‡</b>					
<i>E. coli</i>	332	35	192 (57.8%)	129 (38.9%)	11 (3.3%)
Intestinal enterococci	315	35	145 (46.0%)	141 (44.8%)	29 (9.2%)
Toxigenic <i>V. cholerae</i>	176	26	176 (100.0%)	0 (0.0%)	0 (0.0%)
Total	823	35	513 (62.3%)	270 (32.8%)	40 (4.9%)
<b>Type-approved treatment systems§</b>					
<i>E. coli</i>	310	28	190 (61.3%)	109 (35.2%)	11 (3.5%)
Intestinal enterococci	293	28	142 (48.5%)	123 (42%)	28 (9.6%)
Toxigenic <i>V. cholerae</i>	167	23	167 (100.0%)	0 (0.0%)	0 (0.0%)
Total	770	28	499 (64.8%)	232 (30.1%)	39 (5.1%)
<b>AMS¶</b>					
<i>E. coli</i>	276	25	165 (59.8%)	100 (36.2%)	11 (4.0%)
Intestinal enterococci	268	25	125 (46.6%)	115 (42.9%)	28 (10.4%)
Toxigenic <i>V. cholerae</i>	149	21	149 (100.0%)	0 (0.0%)	0 (0.0%)
Total	693	25	439 (63.3%)	215 (31.0%)	39 (5.6%)

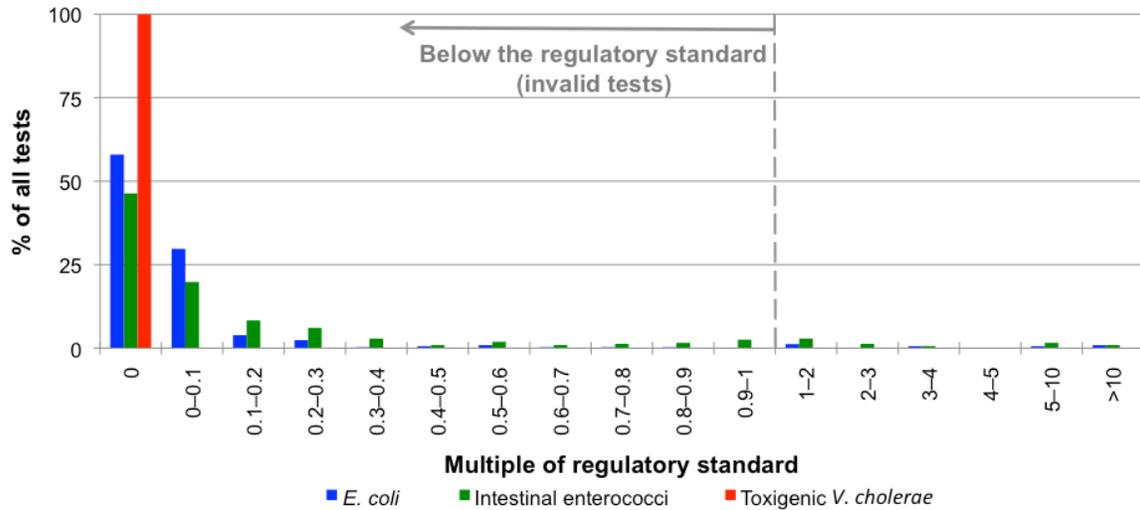
\* IMO, International Maritime Organization

† The distributions of concentrations are provided relative to detection limits and to the IMO/US regulatory limits for ballast water discharges.

‡ All ballast water treatment systems for which test data were publicly available through October 1, 2013.

§ Ballast water treatment systems granted type approval under the IMO Convention.

¶ Ballast water treatment systems accepted as Alternate Management Systems by the US Coast Guard.



**Fig. 1.** Distribution of untreated (control) discharge concentrations. The values shown are *E. coli* (n=332), intestinal enterococci (n=315) and toxigenic *V. cholerae* (n=176) concentrations in untreated discharges in tests conducted according to IMO or US protocols, divided by the IMO/US regulatory discharge limits for these taxa. Values <1 indicate that even without treatment, discharge concentrations met the regulatory discharge limit for that organism. For each indicator microbe, most or all of the untreated discharge concentrations were less than one-tenth of the regulatory discharge limit. Where untreated discharge concentrations exceeded the regulatory discharge limit, most did so by small margins.

The results are similar when the analysis is restricted to treatment systems granted type approval under the IMO Convention, or to treatment systems accepted by the US Coast Guard as AMS. Of the 770 available measurements from tests of type-approved systems, and the 693 available measurements from tests of AMS, the concentrations of regulated microbes in the untreated discharge were below the discharge limits at least 94% of the time and below detection limits at least 63% of the time (Table 2: Type-approved treatment systems and AMS).

We further checked the intake concentrations in trials where untreated discharge concentrations are not available, and the results were generally similar. Of 152 available measurements for any treatment systems, 146 measurements for type-approved systems, and 136 measurements for AMS systems, at least 91% of the intake concentrations were below the regulatory discharge limits and at least 58% were below detection limits (Table S2 in Supplementary Material).

#### 4. Discussion

It has sometimes been argued that ballast water treatment systems do not need to be tested for their ability to kill or remove human pathogens or indicator microbes because many of these systems use disinfection processes—such as chlorination, ozonation or UV treatment—that have been successfully used to kill microbes in drinking water. However, the treatment of ballast water onboard cargo vessels faces two substantial challenges that are not encountered in treating drinking water on land: (a) specific obstacles to treatment efficacy imposed by shipboard conditions, and (b) in the case of bacteria, regrowth within ballast tanks after treatment. Limited space and power, time limitations during short voyages, and ship motions prevent the use on ships of some of the most common and effective processes used to treat water on land, such as

settling tanks and gravity filters. Thus most shipboard systems employ 40- $\mu\text{m}$  or 50- $\mu\text{m}$  metal screen filters, which are much less efficient at removing microbes (most bacteria are  $\leq 1.5 \mu\text{m}$  in diameter) than the filtration processes commonly used to treat drinking water on land. Operation of shipboard treatment systems is additionally hampered by a corrosive environment, cramped working conditions, elevated safety concerns, maintenance and repair challenges, and operation by ships' personnel with limited training in water treatment (Science Advisory Board, 2011).

Nearly all shipboard treatment systems conduct at least part of the treatment during ballast uptake; the treated or partially treated water is then held in ballast tanks for periods lasting from several hours to several weeks or longer. During this time surviving bacteria can multiply and, in some cases, their growth is enhanced by the initial water treatment, which removes and kills organisms that consume bacteria and may break down organic matter and release nutrients that support bacterial growth (Hess-Erga et al., 2010). Thus, some shipboard treatment systems can turn ballast tanks into bacteria incubators. This is confirmed by type approval test results, with bacterial concentrations in treated discharges exceeding those in untreated discharges by up to three orders of magnitude (Table 3).

**Table 3. Effect of selected shipboard ballast water treatment systems on bacterial concentrations in ballast water discharges**

Treatment system	Bacterial measurement*	n†	Trials with increase in bacteria‡	Range of the ratios of the bacterial concentration in treated discharge to the concentration in untreated (control) discharge	Reference
Systems that have been both type approved§ and accepted as AMS¶					
Alfa Laval PureBallast	Culturable bacteria	8	7 (88%)	0.63 to 48	NIVA 2008
	Total bacteria	11	10 (91%)	0.51 to 25	
Ecochlor	Culturable bacteria	11	3 (27%)	<0.014 to 170	NIOZ 2009a
	Total bacteria	14	6 (43%)	0.5 to 1.4	
GEA Westfalia BallastMaster ultraV	Culturable bacteria	14	13 (93%)	0.6 to >1,500	NIOZ 2011
	Total bacteria	10	4 (40%)	0.13 to 2.1	
Hyde Guardian	Culturable bacteria	13	8 (62%)	<0.17 to >37.5	NIOZ 2009b; CBL 2009a
	Total bacteria	11	4 (36%)	0.47 to 8	
Mahle OPS	Culturable bacteria	11	7 (64%)	0.03 to >100	NIOZ 2010
	Total bacteria	11	11 (100%)	1.3 to 6.1	
Systems that have been type approved§					
SEDNA Peraclean	Culturable bacteria	12	10 (83%)	0.4 to >1,000	NIOZ 2008
	Total bacteria	11	11 (100%)	1.3 to 6.1	
Other systems					
Siemens SeaCURE	Culturable bacteria	13	11 (100%)	6.5 to 4,800	CBL 2009b, 2010; GSI 2010

\* Measured either as total bacteria (by flow cytometry using DNA stains) or as culturable bacteria (by plate counts of colony-forming units of heterotrophic bacteria on standard growth media).

† The number of trials.

‡ The number and percentage of trials in which the bacterial concentration in the treated discharge was greater than the concentration in the untreated (control) discharge.

§ Ballast water treatment systems granted type approval under the International Maritime Organization Convention.

¶ Ballast water treatment systems accepted as Alternate Management Systems by the US Coast Guard.

Given the obstacles to effective shipboard treatment and the potential for enhanced bacterial growth within ballast tanks, effective implementation of regulatory standards that limit the release of microbial pathogens is essential. The IMO Convention created a certification program for shipboard ballast water treatment systems that relies on formal testing to verify treatment systems' ability to reduce the discharge of microbes to levels that protect public health. A similar testing and certification program has been adopted to support US regulations. However, our review of the first 10 years of test data shows that the protocols for the microbe tests are defective, and the tests are largely meaningless. In these tests a treatment system is reported as passing if the organism concentrations in the treated discharges do not exceed the regulatory discharge limits. Thus, in order for these tests to provide information about the treatment systems' ability to reduce the discharge of regulated microbes, the concentrations of these microbes in the untreated (control) discharge water must, at a minimum, exceed the discharge limits. Our analysis shows that this condition was not met in 95% of the 770 available results from microbial tests of type-approved treatment systems, and 94% of the 693 available results from microbial tests of AMS.

In each of these cases the treatment system was reported as having passed the test, and in each case the treatment system was granted type approval or AMS status based on the test results. However, few of these exercises were, in fact, tests, since in nearly all cases it was impossible to fail them. Because the concentrations in the untreated discharges were below the discharge limits, the treatment systems would have equally well passed these "tests" even if they had never been turned on. To put it another way, the tests as applied were incapable of distinguishing between treatment systems that reduced target microbe concentrations and treatment systems that did not.

Although it might be possible to learn something about treatment system performance by comparing the counts of target microbes in treated and untreated discharges even in the tests (about 30% of the total) where the untreated discharge concentrations were below regulatory limits but above the detection limits, or by comparing these counts for the taxonomically broader surrogates reported in some tests (*e.g.* counts of coliform bacteria or thermotolerant coliform bacteria—reported in about 10% of the trials—rather than counts of *E. coli*), we emphasize that the determination by test laboratories of whether treatment systems passed these tests, and the consequent awarding of type approval by IMO member states, was not based on such comparisons. Our analysis here is only on whether the tests as they are actually conducted and used provide a meaningful assessment of treatment system performance.

While we make no attempt here to assess whether the discharge standards adopted by the IMO and the United States are adequate to protect the public health, we note that these standards do not include limits on the discharge of total bacteria or viruses, as do standards enacted by the State of California (California, 2006), nor do they contain limits on the discharge of pathogenic and toxigenic protists less than 10  $\mu\text{m}$  in size, as recommended by the US EPA's Science Advisory Board (Science Advisory Board, 2011). With no general limits on the discharge of bacteria, viruses or small protists, the three specific microbes targeted by the IMO and US standards must serve as regulatory proxies for all microbial pathogens, and rigorous implementation of the limits on these indicator microbes is therefore especially critical.

These limits were adopted specifically to reduce the health risk from ships that load ballast water from coastal or river waters contaminated with untreated sewage or containing high concentrations of pandemic *V. cholerae*. To assess the ability of treatment systems to perform adequately under those conditions, it is not enough to test them with water that just exceeds the

discharge requirements, the question that we analyzed here. Rather, treatment systems must be tested with water that reflects the challenging conditions in which ships are expected to operate (Hunt et al., 2005). Appropriate test concentrations might be on the order of  $10^5$ - $10^6$  cfu/100 mL of *E. coli* and  $10^3$ - $10^4$  cfu/100 mL of intestinal enterococci in intake waters, based on concentrations found in some polluted surface waters (Joachimsthal et al., 2004; Haugland et al., 2005; McQuaig et al., 2006). Although conducting trials with high concentrations of toxigenic *V. cholerae* is not advisable, it should be feasible to use a surrogate such as another *Vibrio* species. Appropriate test concentrations might then be on the order of  $10^8$  cfu/100 mL, equal to the *V. cholerae* concentrations reported in the ballast tanks of one-third of the tested vessels that arrived in US waters from Latin America during the 1991 cholera epidemic (McCarthy and Khambaty, 1994). Out of the 831 relevant measurements (intake or untreated discharge) that we analyzed, only 18 of the enterococci concentrations and none of the *E. coli* or *V. cholerae* concentrations reached these levels (Table S1 in Supplementary Material). If it is impractical or unsafe to test treatment systems in waters where the concentrations of target microbes or surrogates are sufficiently high, or to add target microbes or surrogates to achieve adequate concentrations in test waters, then some other method to test for the appropriate level of performance should be sought.

Since neither IMO nor US test protocols require any minimum concentration of indicator microbes in intake or control discharge water, even tests in which those microbes were completely absent were considered by the test facilities to be valid, and treatment systems were granted IMO type approvals or approved for use in US waters based on those tests. If the goal is to prevent the spread of human disease via ballast water, then the test protocols must be revised to require minimum concentrations of target organisms that reflect the conditions of concern in which ballast water treatment systems will operate, and nearly all the approved treatment systems will need to be retested. Otherwise, the failure to control the dissemination of microbes in ballast water will needlessly expose human populations to increased risk of epidemics of waterborne disease.

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This paper is offered in memory of Florence Cohen, who loved the ocean.

## Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version, at <http://dx.doi.org/10.1016/j.marpolbul.2014.12.031>

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