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# Revisiting the basis for US ballast water regulations

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ABSTRACT

The transport and release of invasive organisms in ballast water has harmed ecosystems, economic activities and human health. Current US ballast water regulations intended to minimize the discharge of such organisms are based on results reported by a scientific advisory committee in 2011. Using the same methods, we re-analyzed the data evaluated by the committee as well as new data. We find that the committee's analysis was flawed, and that some treatment systems can meet limits that are 10 times (for zooplankton) or 1000 times (for phytoplankton) more stringent than the committee reported. These findings suggest that US ballast water standards, and similar standards in a recently ratified international agreement, should be re-evaluated.


## 1. Introduction

The spread of aquatic organisms around the world in ships' ballast water has harmed ecosystems, disrupted economic activities, and sickened and sometimes killed people (Carlton, 1985; Epstein et al., 1993; McCarthy and Khambaty, 1994; Hallegraeff, 1998). In 2004 the International Maritime Organization (IMO) drafted an international treaty (the Ballast Water Convention) that requires signatory nations to implement limits on the discharge of two groups of organisms and three indicator microbes, known as the IMO D-2 discharge standard. The Convention will enter into force in September 2017.

The United States has not signed the Convention, but instead regulates ballast discharges under laws implemented by the U.S. Coast Guard (USCG) and U.S. Environmental Protection Agency (USEPA). In 2010 these agencies jointly convened a Ballast Water Advisory Panel under the auspices of the USEPA's Science Advisory Board (SAB), to determine what level of ballast water treatment is possible.[1] The Panel and SAB reported that the available test data showed there were several types of treatment systems that could meet the IMO D-2 standard but failed to show that any treatment system could meet a standard ten times as stringent (referred to as 10x IMO D-2) (SAB, 2011). Based on those results, in 2012 and 2013 USCG and USEPA adopted discharge limits incorporating the IMO D-2 standard.

While reviewing data for a related study (Cohen and Dobbs, 2015), we realized that the test data examined by SAB appeared to contradict SAB's conclusion that no treatment system had demonstrated the ability to meet the 10x IMO D-2 standard. We here analyze the same test data examined by SAB, using the same methods, to determine whether the results match those reported by SAB. In addition we analyze test data that have become available since SAB conducted its analysis, to determine whether more recent data alter the results.

## 2. Methods

### 2.1. Test data

The Ballast Water Convention requires shipboard ballast water treatment systems to be tested and certified as capable of meeting the IMO's discharge limits, a process known as type approval. SAB (2011) reviewed the type approval test results available through December 1, 2010, which we refer to as the "SAB Data." SAB determined that the data for 9 treatment systems were reliable and analyzed the data for 8 of them, excluding one treatment system that had been withdrawn from the market. Data rated reliable included results from land-based or shipboard testing that used reasonable and appropriate methods and QA/QC procedures and produced credible results.

To determine whether SAB's conclusions were correct, we analyzed the same data for the same 9 treatment systems considered by SAB, using the same analytical method (described below). Because SAB reported results in terms of operational types rather than treatment systems (see below), and the ability of an operational type to meet a standard is not affected by whether a treatment system of that type is currently available on the market, we retained in our data sets the treatment system that SAB excluded from analysis because it had been withdrawn from the market.

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To determine whether analysis of more recent data would produce a different result, we obtained additional test reports for shipboard treatment systems through: internet searches; inquiries of equipment manufacturers, test laboratories, and the government agencies or agents that grant type approvals; Freedom of Information Act requests submitted to USCG; and a Public Records Act request submitted to the California State Lands Commission. We obtained information on detection limits from the test laboratories, or determined detection limits from the test reports and associated documents (see Detection Limits in Supplementary material). To the test data that SAB determined to be reliable (the SAB Data), we added the new data available through September 25, 2016 to produce a database we refer to as "All Data". We excluded treatment systems for which only shipboard test data were available, and systems whose data did not meet SAB's reliability criteria, including consideration of appropriate methods and QA/QC procedures. Treatment systems included in the database are listed in Table S2 in Supplementary material, with citations for the test reports, QA/QC documentation, and other relevant documents.

### 2.2. Analysis

SAB (2011) assessed the performance of shipboard ballast water treatment systems in terms of four discharge standards (Table 1). The first, the IMO D-2 standard, limits the concentrations of two organism groups and three indicator microbes in treated discharges. The two organism groups are based on size: the larger group comprises organisms whose minimum dimension is greater than or equal to 50 μm (hereafter the "≥50 μm group") and mainly consists of zooplankton, while the smaller group comprises organisms whose minimum dimension is greater than or equal to 10 μm and less than 50 μm (hereafter the "10–50 μm group") and mainly consists of phytoplankton. The other three standards—designated 10x IMO D-2, 100x IMO D-2 and 1000x IMO D-2—refer to concentration limits that are 10 times, 100 times, or 1000 times lower (*i.e.*, more stringent) than the limits in IMO D-2 for one or both of these organism groups (Table 1). The indicator microbe limits are the same in all four standards (see Definitions of Standards in Supplementary material).

SAB (2011) assessed whether treatment systems had demonstrated the ability to meet a given standard using two separate protocols: the G8 Guidelines (IMO, 2008), which are used to assess treatment systems for type approval under IMO's Ballast Water Convention; and the ETV Protocol (USEPA, 2010), used to assess treatment systems for US type approval. The G8 Guidelines base assessment on 10 land-based trials in 2 salinity ranges plus 3 consecutive shipboard trials. The ETV Protocol bases assessment on 6 land-based trials in 2 salinity ranges, and doesn't address shipboard trials. Where data for fewer trials were available, SAB based its assessment on the available data. SAB categorized treatment systems by operational type, and for each operational type reported the results for the treatment system with the best performance, representing the highest level of treatment that the operational type had achieved. Although a chapter in SAB's report discusses approaches for assessing the statistical certainty of results in monitoring or testing based on organism counts and volumes analyzed, no such analysis is mentioned in the methods section. SAB's methods instead base assessment on the G8 Guidelines—which state that a treatment system is deemed to meet the standard for an organism group if the average concentration in the treated discharge samples in each required trial is below the concentration limit (IMO, 2008, Annex §2.3.5)—or the ETV Protocol.

**Table 1**
Treated discharge concentration limits for the organism groups in the analysis.

| Organism group | IMO D-2 | 10x IMO D-2 | 100x IMO D-2 | 1000x IMO D-2 |
|---|---|---|---|---|
| ≥50 μm | 10/m$^3$ | 1/m$^3$ | 0.1/m$^3$ | 0.01/m$^3$ |
| 10–50 μm | 10/mL | 1/mL | 0.1/mL | 0.01/mL |

We used these same methods and standards to assess both the SAB Data and All Data, with two adjustments. First, the IMO D-2 standard limits the concentrations of "viable" organisms in discharges while US regulations limit the concentrations of "living" organisms. In tests of ballast water treatment systems, viable photoautotrophs in the 10–50 μm group are counted by observing growth in an appropriate medium after serial dilutions, often referred to as the Most Probable Number or MPN method; living organisms are counted using stains to distinguish live from dead cells. The viable organism (MPN) method generally yields a lower count than the living organism (staining) method (Casas-Monroy et al., 2016). SAB (2011) does not state how these different analytical results were used in its assessment. To assess compliance with the standards in accordance with IMO's G8 Guidelines, for both SAB Data and All Data, we used viable organism counts if available; if not, we used living organism counts; and if these were not available, we used counts of chlorophyll-containing cells (based on chlorophyll autofluorescence) or counts of intact cells, which include both live and dead cells. To assess compliance in accordance with the ETV protocol, we used living organism counts if available; if not, we used chlorophyll-containing or intact cell counts. If microzooplankton in the 10–50 μm size range were counted separately, we added those to the above counts.

Second, after the SAB report was published, USCG (2012) adopted type approval regulations requiring treatment systems to meet discharge standards in 5 consecutive shipboard trials as well as the 6 land-based trials required by the ETV Protocol. We used these requirements as the basis for assessing All Data, but used the ETV Protocol requirements alone (as did SAB) to assess the SAB Data. For both data sets, we refer to the basis for these assessments as the "US Protocol," and the basis for assessments in accordance with IMO's G8 Guidelines as the "IMO Protocol."

We report results both for individual treatment systems and operational types, and compare our results to the results in SAB (2011).

## 3. Results

### 3.1. SAB Data

SAB (2011) rated the data for 9 ballast water treatment systems as reliable. Excluding one system that had been withdrawn from the market, SAB found that 7 of the 8 remaining treatment systems, representing 5 operational types, had met the IMO D-2 standards consistent with both the IMO and US Protocols. SAB further reported that the test data showed that none of the treatment systems or operational types had demonstrated the ability to meet the 10x IMO D-2 standard, although with reasonable improvements they might have potential to meet that standard; and that all treatment systems had failed to meet the 100x IMO D-2 standard by such large margins that even with reasonable improvements they still would not meet the 100x IMO D-2 standard, and wholly new types of treatment systems would be needed instead.

However, our analysis of the same data using the same methods found that 2 of the 9 treatment systems, representing 2 operational types, met the 10x IMO D-2 standard for the ≥50 μm organism group when assessed using the IMO protocol; and 4 systems, representing 4 operational types, met that standard when assessed with the US Protocol (Figs. 1, 2). Five (IMO Protocol) and 4 (US Protocol) treatment systems and operational types met the 10x IMO D-2 standard for the 10–50 μm organism group. Several treatment systems approached compliance with the 100x IMO D-2 standard, especially for the 10–50 μm organism group. Two (IMO Protocol) or 3 (US Protocol) treatment systems and operational types met the 10x IMO D-2 standard for both organism groups.

Table 2 provides the test results for one of these treatment systems. Concentrations of ≥50 μm organisms were 0.33/m$^3$ in 2 of 10 trials (1 organism detected in 3 m$^3$ of water in each trial) and less than the

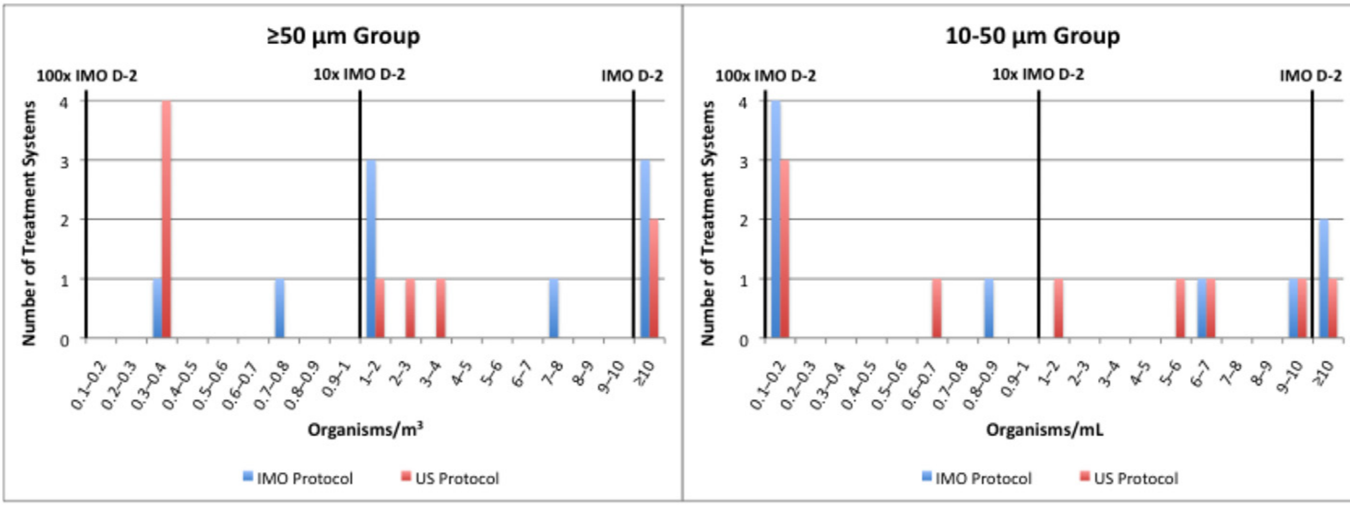


**Fig. 1.** Standards met by treatment systems, based on SAB Data. X-axis bins are defined as ≥ the lower boundary and < the upper boundary.

detection limit of $0.33/m^3$ in 8 of 10 trials (no organisms detected). These results meet the 10x IMO D-2 standard of $<1$ organism/$m^3$ for this organism group, whether assessed by the IMO Protocol or the US Protocol. Similarly, concentrations of 10–50 µm organisms were below the detection limit of 0.11/mL in all 10 trials. These results meet the 10x IMO D-2 standard of $<1$ organism/mL for the 10–50 µm organism group, and approach the 100x IMO D-2 standard of $<0.1$ organism/mL, whether assessed by the IMO or US Protocol.

### 3.2. All Data

We obtained data for 60 treatment systems, including 58 of the 65 treatment systems that have been type approved under IMO's Ballast Water Convention (Table S2 in Supplementary material). For the ≥50 µm group, 8 treatment systems representing 7 operational types (IMO Protocol), and 11 systems representing 7 operational types (US Protocol) met the 10x IMO D-2 standard (Figs. 3, 4).

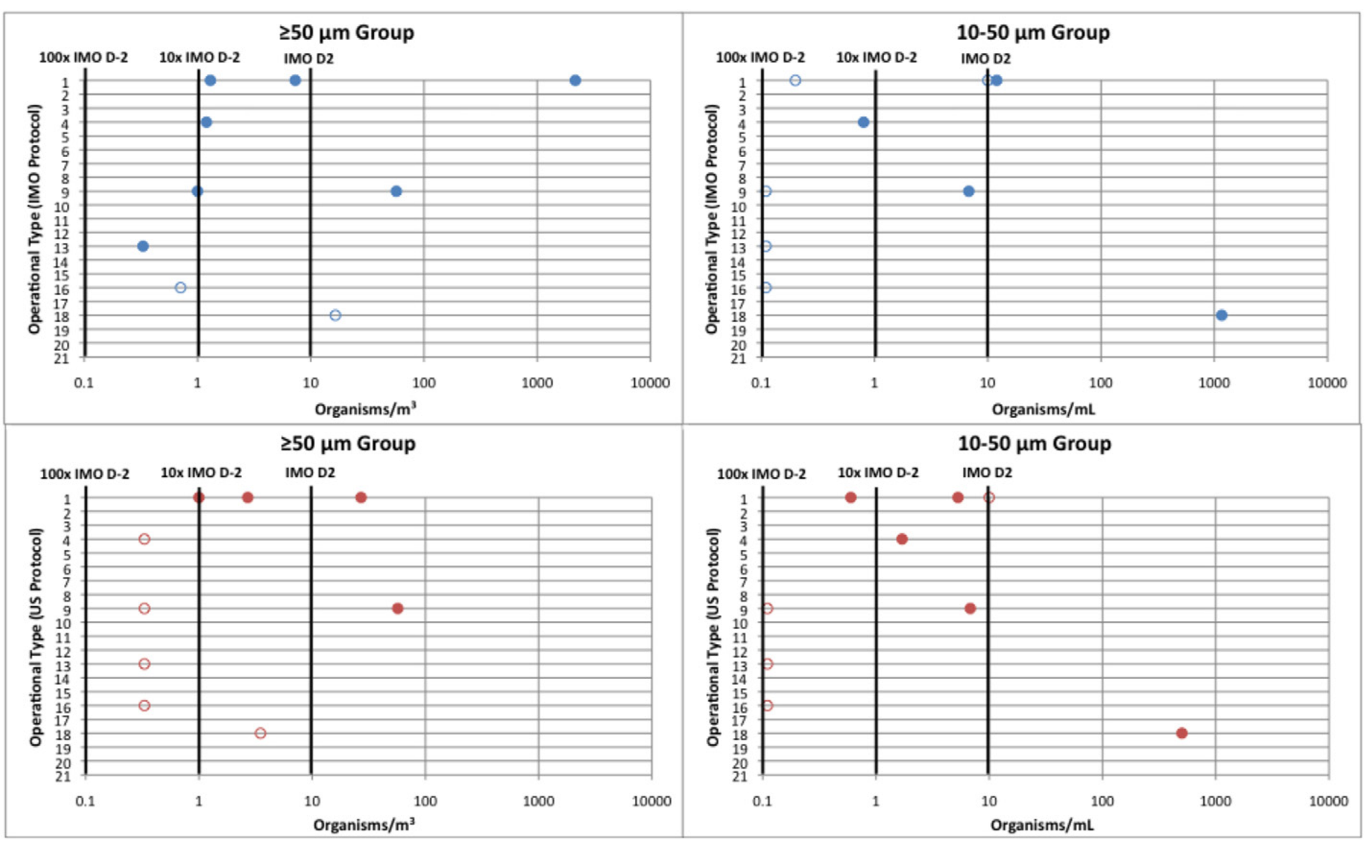


**Fig. 2.** Standards met by operational types, based on SAB Data. An open circle indicates that the organism concentrations were below these detection limits in all trials included in the analysis; a closed circle indicates a concentration above the detection limit. Operational types are: 1. Filtration + UV, 2. Hydrocyclone + Filtration + UV, 3. Filtration + UV + Ozone Injection, 4. Filtration + UV + Titanium Dioxide, 5. Filtration + UV + Ultrasound, 6. Filtration + UV + Plasma, 7. Pressure Drop + UV, 8. Electrochemical Oxidation, 9. Filtration + Electrochemical Oxidation, 10. Hydrocyclone + Electrochemical Oxidation, 11. Filtration + Electrochlorination + Ozone Injection, 12. Filtration + Chlorine Injection, 13. Filtration + Chlorine Dioxide Injection, 14. Ozone Injection, 15. Peracetic Acid/Hydrogen Peroxide Injection, 16. Hydrocyclone + Filtration + Peracetic Acid/Hydrogen Peroxide Injection, 17. Membrane Filtration + Deoxygenation, 18. Deoxygenation + Cavitation, 19. Deoxygenation + Heat, 20. In-tank Deoxygenation, 21. Membrane Filtration.

**Table 2**
Live organism concentrations in treated discharge in tests of the Ecochlor ballast water treatment system.[a]

| Trial[b] | ≥50 μm organisms[c] ($m^{-3}$) | 10–50 μm organisms[c] ($mL^{-1}$) |
|---|---|---|
| 7 | <0.33 | <0.11 |
| 8 | 0.33 | <0.11 |
| 9 | 0.33 | <0.11 |
| 10 | <0.33 | <0.11 |
| 11 | <0.33 | <0.11 |
| 12 | <0.33 | <0.11 |
| 13 | <0.33 | <0.11 |
| 14 | <0.33 | <0.11 |
| 15 | <0.33 | <0.11 |
| 16 | <0.33 | <0.11 |

[a] Data from NIOZ (2009), Tables 8 and 9. No shipboard test data were available to SAB.
[b] Trials 1–5 were conducted without a filter and Trial 6 at less than the system's standard dosage; the results from these trials were not included in the analysis.
[c] We list results to 2 significant digits based on analyzed volumes of 3 $m^3$ for ≥50 μm organisms and 9 mL for 10–50 μm organisms.

For the 10–50 μm group, based on the IMO protocol, 19 treatment systems representing 11 operational types met the 10x IMO D-2 standard; another 3 systems representing 3 types met the 100x IMO D-2 standard; and 3 additional systems representing 1 type met the 1000x IMO D-2 standard. Based on the US protocol, 18 treatment systems representing 10 operational types met the 10x IMO D-2 standard; another 6 systems representing 6 types met the 100x IMO D-2 standard; and 2 systems representing 1 type met the 1000x IMO D-2 standard (Figs. 3, 4).

Considering the ≥50 μm and the 10–50 μm groups together, based on the IMO protocol 7 treatment systems met at least the 10x IMO standard for both groups; of these, 1 met the 100x IMO standard and 1 met the 1000x IMO standard for the 10–50 μm group. Based on the US protocol, 9 treatment systems met at least the 10x IMO standard for both groups; 3 of these met 100x and 1 met 1000x IMO for the 10–50 μm group.

## 4. Discussion

The SAB is one of the premier scientific bodies in the US government. Established by order of Congress in 1978, it reviews the scientific and technical basis for USEPA regulations, research programs and plans, and provides science advice to USEPA. SAB currently includes 151

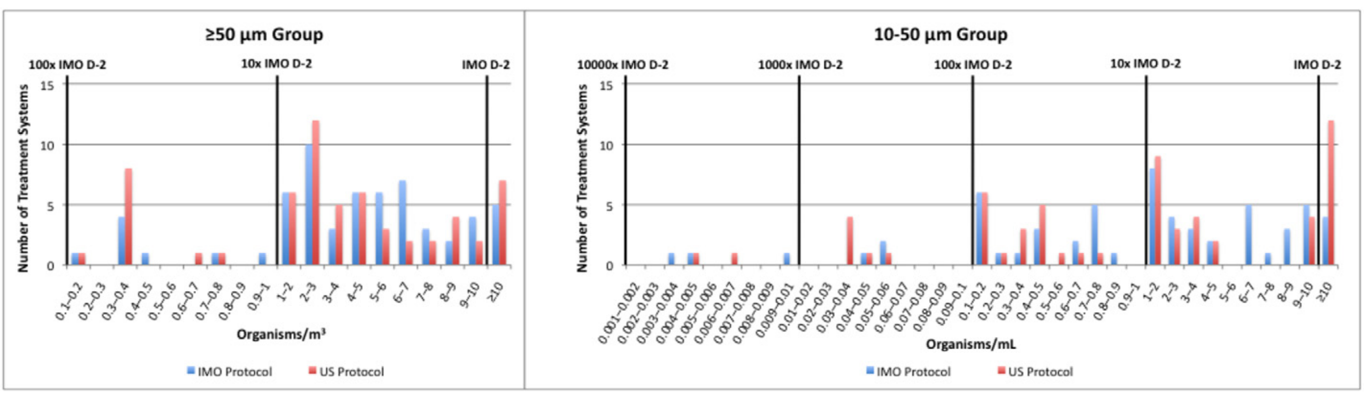


**Fig. 3.** Standards met by treatment systems, based on All Data. X-axis bins as in Fig. 1.

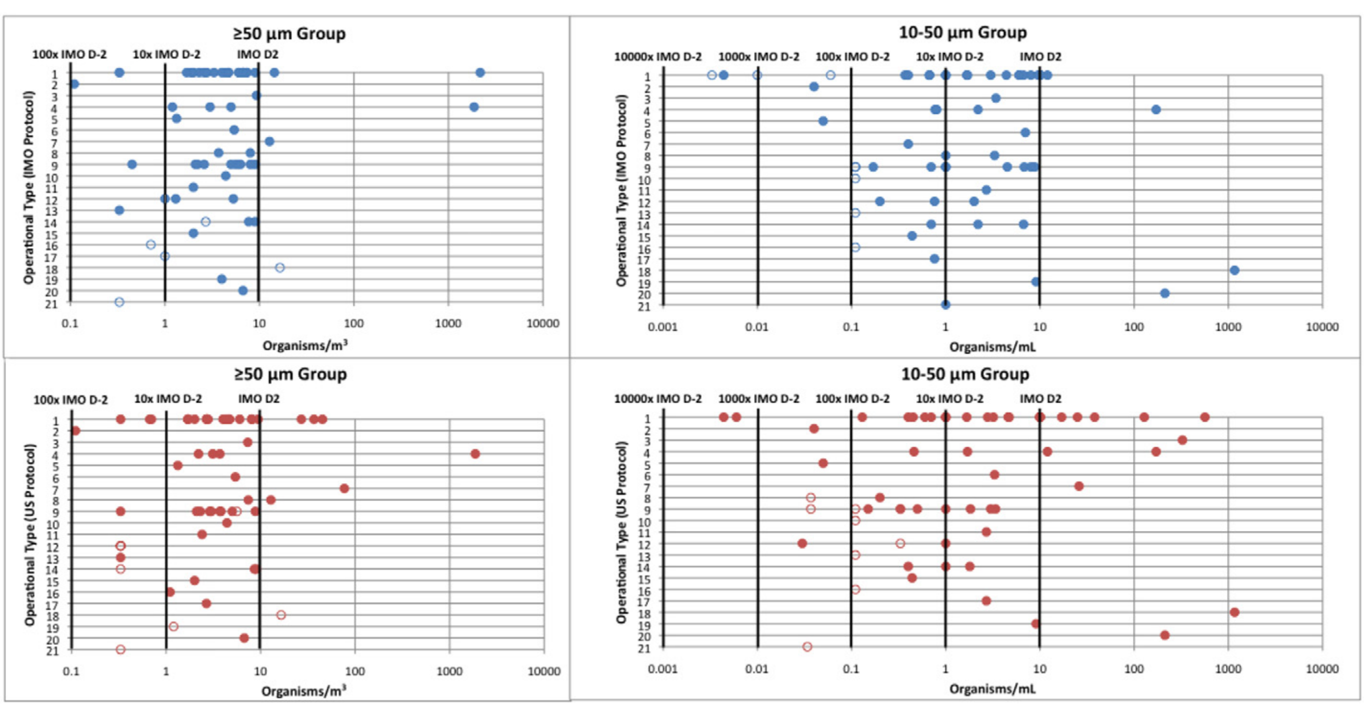


**Fig. 4.** Standards met by operational types, based on All Data. An open circle indicates organism concentrations were below this detection limit in all relevant trials; a closed circle indicates a concentration above the detection limit. Some data points overlay others. Operational types are as in Fig. 2.

independent scientists serving on the Chartered SAB Committee and six permanent standing committees, plus additional scientists serving on *ad hoc* panels and committees (USEPA, 2016a).

In 2011 SAB assessed the performance of ballast water treatment technologies as guidance for revising USCG's ballast water regulations and USEPA's Vessel General Permit (VGP), which regulates ships' discharges into US waters. Reviewing the available test data, SAB concluded that several ballast water treatment systems met the IMO D-2 standard, none demonstrated meeting the 10x IMO D-2 standard, and that even with improvements none could meet the 100x IMO D-2 standard. In March 2012 USCG adopted discharge regulations and in June 2012 USEPA issued a new VGP, both of which incorporated organism concentration limits identical to those in the IMO D-2 standard. Both agencies stated that these limits were “the most stringent standards” that ballast water treatment could meet, citing SAB's report as the source for this conclusion (USCG, 2012; USEPA, 2013).

In the present study we assessed all currently available test data and re-assessed the 2010–11 data, employing the same methods as SAB. The results based on current data are inconsistent with SAB's conclusions. Whichever protocol is used, at least 13% of the 60 treatment systems met the 10x IMO D-2 standard for the larger organism group, at least 42% met the 10x IMO D-2 standard or more stringent standards for the smaller organism group, and at least 12% met the 10x IMO D-2 standard for both organism groups. The results are also inconsistent with SAB's conclusions even if only the data reviewed and deemed reliable by SAB are analyzed, wherein at least 22% of the treatment systems met the 10x IMO D-2 standard for the larger organism group, at least 44% for the smaller organism group, and at least 22% for both groups.

In March 2015, with three other members of SAB's former Ballast Water Advisory Panel, we informed USEPA and USCG that the data examined by the SAB did not support the reported conclusions. Some members of the former Panel argued that our re-analysis is flawed (USEPA, 2016b). None disputed that the test results for some treatment systems are below the 10x IMO D-2 limits and at least close to the 100x IMO D-2 limits for one or both of the organism groups. They argued, however, that while those results demonstrated compliance with the IMO D-2 standard, they were inappropriate to use as indicators of compliance with 10x IMO D-2 or more stringent standards. Similar arguments were raised by a Work Group convened by SAB in 2016 to consider whether the SAB report's conclusions were false.

One argument was that statistical analysis showed the volumes of water analyzed were too small to provide sufficient confidence that the average organism concentrations in the discharges were below the 10x IMO D-2 limits. However, no such analysis is mentioned in SAB's methods, and the range in performance between the treatment systems was so great that there is no minimum required confidence level that would support both a finding that 5 operational types met IMO D-2 and a finding that none of them met 10x IMO D-2 (see Regarding an Analysis of Confidence in Supplementary material).

Some former Panel members and the SAB Work Group cited statements in SAB (2011) that the detection limits in the available test data “preclude a complete statistical assessment” of whether treatment systems met the 10x IMO D-2 limits, or that the “resolution” or “precision” of the data were inadequate, arguing that these statements provide authority for rejecting the test results. However, SAB (2011) provides no evidence or source for these statements. With their reference to statistical assessment, they appear to refer to the inadequate confidence argument described above, which, as noted, is incorrect if applied to the test results considered by SAB and therefore also wrong as a general statement about available test methods. The detection limit for the methods used in these tests—counting individual organisms in a volume of water—is the reciprocal of the water volume analyzed (First and Drake, 2014). For the treatment systems whose test results we found had met 10x IMO D-2, the detection limits are well below the 10x IMO D-2 concentration limits, and thus offer no obstacle to assessing compliance with those limits (see Detection Limits and Table S1 in Supplementary material).

The SAB Work Group argued that the volumes sampled in the tests were smaller than the sample volumes “required” for analysis of the ≥50 μm group at the 10x IMO D-2 level, as listed in a table in a section of the SAB report titled “Theoretical Considerations.” However, as the table caption states, the table simply provides examples of the sample volumes that would be required *if* the sample is concentrated to a certain specified degree *and if* a certain number of subsamples of a specified size are analyzed, *and if* the minimum acceptable confidence level is set at a specified percentage. Since none of the tests included in SAB Data or All Data sampled, concentrated the samples, or subsampled as described in the table, the required volumes listed in the table don't apply to these tests. Also, if the table did apply to these tests, it would also invalidate the SAB report's conclusion that 5 operational types met the IMO D-2 standard, since the sample volumes in the SAB Data tests were smaller than the required volumes listed in the table for analysis at the IMO D-2 level. In a similar vein, the Work Group argued that 1 $m^3$ sample volumes are too small to assess compliance for the ≥50 μm group at the 10x IMO D-2 level. However, the tests that reported discharge concentrations below the 10x IMO D-2 standard sampled and analyzed volumes larger than 1 $m^3$.

Another argument made by some former Panel members was that the laboratories conducting the tests “lacked any sort of quality management system” or “proper QA/QC.” The treatment system tests considered by SAB whose results met 10x IMO D-2 were conducted by the Royal Netherlands Institute for Sea Research (NIOZ), the Norwegian Institute for Water Research (NIVA) and the University of Maryland's Chesapeake Biological Laboratory. SAB determined that these test results were reliable, with the determination including consideration of QA/QC procedures (SAB, 2011, pp. 30–35). The test reports cite test plans and Quality Assurance Project Plans where the quality management procedures are described in detail. There is thus no basis for the charge that these tests lacked any sort of quality management. If they had, it would be as inappropriate to use them to assess compliance with the IMO D-2 standard (as SAB did) as to use them to assess compliance with the 10x IMO D-2 standard.

Yet another argument was that the sampling approaches in these tests “have since been deemed inadequate” and the analytical methods “have never been validated.” As noted, SAB determined that the test results were reliable, based in part on finding that the tests were “conducted with reasonable and appropriate methods,” that “analytical facilities were adequate,” and that the tests “produced credible results.” While it is true that the sampling and analytical methods are imperfect, as is true of all methods, the test results nonetheless provide information that can reasonably be used to assess treatment system performance. Had the sampling and analytical methods been inadequate or invalid, it would be equally inappropriate to use the results to assess the IMO D-2 standard as the 10x IMO D-2 standard.

In March 2016 it was argued that the fact that USCG had not type approved a single treatment system as meeting US discharge standards was “counter to the claims” that some treatment systems performed better than those standards. However, the lack of US type approvals at that time didn't have anything to do with the limits of treatment system performance. Rather, until 2015 no manufacturer had completed land-based and shipboard tests that comply with US protocols, and none submitted an application for type approval until September 2016. USCG could not legally grant type approval to a ballast water treatment system before receiving the treatment system's application. Since September 2016, USCG has type approved 3 treatment systems.

A final, frequently raised argument was that the analysis should be conducted with the most recent available data. That analysis, included here, provides further evidence that SAB's conclusions are incorrect.

## 5. Conclusions

SAB's (2011) conclusions regarding ballast water treatment, on which current US ballast water regulations are based, are here shown to be incorrect. Based on the data available to SAB in 2011, some existing treatment systems were capable of meeting standards 10 times and possibly 100 times more stringent than SAB stated. More recent data show some treatment systems doing even better. These results have implications both for US ballast water regulations, which are explicitly based on SAB's incorrect results, and for the International Ballast Water Convention, due to go into effect later this year. Although the present analysis includes some test data for nearly all approved treatment systems, the US and the Convention's signatory nations could make more comprehensive assessments possible by releasing all test reports used to approve treatment systems.

## Contributors

A.N.C. compiled the data and conducted the analysis, and F.C.D. and P.M.C. checked the analysis. All authors collaborated in drafting the manuscript and approved the final manuscript.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.marpolbul.2017.03.020.

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