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How many organisms are in ballast water discharge? A framework for validating and selecting compliance monitoring tools

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ABSTRACT

As regulations governing the discharge of living organisms in ships' ballast water enter into force, tools to rapidly and easily measure compliance with the discharge standards will be essential. To assess, validate, and select compliance tools, a framework—consisting of three parts—is presented: proof-of-concept, validation and verification, and final selection stages. Next, a case study describing the proof-of-concept stage is discussed. Specifically, variable fluorescence was evaluated as an approach for determining compliance with the discharge standard for living organisms ⩾10 μm and <50 μm (typically protists). Preliminary laboratory experiments were conducted, which were followed by an expert workshop to gauge the feasibility of this approach and propose hypothetical thresholds indicating when the discharge standard is undoubtedly exceeded. Subsequently, field trials were conducted to assess this approach and recommended thresholds. All results were favorable, indicating the validation and verification stages are merited to further evaluate fluorometers as compliance monitoring tools.

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1. Introduction

The international maritime industry transports approximately 90% of the world's commodities and is fundamental to world trade (IMO, 2012b). An unintended consequence of this trade is the transport and delivery of organisms from one location to another via ballast water, which is carried by vessels to control draft, stability, and trim (e.g., Medcof, 1975; Carlton, 1985; National Research Council of the National Academies, 2011). In the 1980s, attention was focused on this global environmental issue following the introduction of aquatic nuisance species presumed to have been transported in ballast water, such as the introductions of the Zebra Mussel, *Dreissena polymorpha*, to the North American Great Lakes and the Atlantic Comb Jelly, *Mnemiopsis leidyi*, to the Black Sea. International, national, and regional action followed. The International Maritime Organization (IMO) adopted an international convention (IMO, 2004), which remains to be ratified sufficiently to enter into force. In the U.S., several legislative and executive actions governing ballast water discharges were promulgated between 1990 and 2013 (USCG, 2012; EPA, 2013). Both the IMO and U.S. actions aim to limit the number of living organisms discharged in ballast water, allowing: (1) <10 organisms ⩾50 μm in size (typically dominated by zooplankton) per m^3, (2) <10 organisms ⩾10 μm and <50 μm in size (typically dominated by protists, often phytoplankton) per mL, and (3) limits on indicator and pathogenic bacteria per 100 mL (<250 colony forming units [cfu] of *Escherichia coli*, <100 cfu of intestinal enterococci, and <1 cfu of toxigenic *Vibrio cholerae*). To meet these stringent discharge standards, most vessels will install onboard a "ballast water management system" (BWMS). Of the BWMSs currently installed on vessels, or those in development, most treat water using a combination of physical separation (e.g., filtration) followed by a disinfection step (e.g., electrochlorination or UV radiation).

As the IMO convention and the U.S. regulations enter into force, a process for determining a vessel's compliance upon arrival in port will need to proceed quickly, so as not to impede commerce. To that end, initial determinations of compliance will likely be made without directly enumerating the exact number of all living organisms in the ballast water discharge. For example, phased compliance monitoring approaches, which provide increasing levels of confidence, have been proposed (IMO, 2008, 2009; King and Tamburri, 2010).

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While the exhaustive sampling and analysis protocols currently used to verify BWMS performance (e.g., EPA, 2010) would provide the highest level of confidence that a discharge is in compliance (or not) with the discharge standards, the constraints of time, logistics, and costs likely make these approaches unrealistic for routine vessel monitoring (King and Tamburri, 2010). Thus, if the ballast water is evaluated, an "indicative analysis" may occur (IMO, 2008, 2009). In this case, rapid, direct or indirect measures of treatment by appropriate functioning of BWMSs (e.g., measuring the pressure differential around filters or the concentration of residual chemicals) could be assessed, or the groups of organisms prescribed by the discharge standard could be considered. On the other hand, "detailed" analyses would be completed in a more comprehensive manner and likely require more time and a higher level of expertise than indicative analyses (IMO, 2009). Given that indicative analyses are intended to be quick, initial checks of the ballast water, tools used in these measurements would be expected to show only whether the discharge standards were clearly exceeded (e.g., 10× or 100× greater than allowed). Further, such tools may employ bulk metrics (e.g., the concentration of chlorophyll *a* or ATP) to *estimate* the concentration of living organisms rather than *directly enumerate* the number of living organisms. Regardless, the data collected in this rapid analysis may be sufficient to show a vessel's ballast water is clearly not in compliance with the discharge standard, and thus, no further sampling and analysis would be warranted. This paper focuses on a process of assessing and verifying compliance monitoring tools used in indicative analyses (rather than detailed analyses) to determine compliance with the discharge standard adopted by the IMO and the U.S. Here, tools are hand-held devices used by port state control officers to rapidly assess ballast water during vessel inspections, rather than autonomous, in-line sensors installed on a vessel or within a BWMS.

At present, no means to quickly evaluate ballast water for compliance with discharge standards (here, indicative analysis) are in use, and while various tools are under development, there is no widely accepted framework by which to formally evaluate and choose tools for use in a regulatory enforcement application. It is critical to close this gap. The uncertainty surrounding compliance testing is one of the significant barriers to the ratification and entry into force of the IMO Ballast Water Management Convention (e.g., IMO, 2012a). Thus, the lack of tools for compliance testing has helped stall the implementation of international policy, and subsequently, the fleet-wide installation of ballast water management systems aboard approximately 60,000 vessels, projected to be a $3.14 billion industry by 2023 (Frost and Sullivan, 2013).

The assessment of compliance tools differs from most validation exercises, owing to the knotty nature of the ballast-water issue. First, because vessels may contain ballast water from any port in the world, the appropriate tool(s) must be able to interrogate samples across an extremely broad range of organisms and water-quality characteristics. Second, the users of the compliance tools will be neither scientists nor technicians but port state control officers with little time for scientific training along with the many other duties they perform. Finally, and most important, the compliance tools will need to consistently generate accurate, credible decisions indicating a clear failure to meet the discharge standards, and these assessments can incur substantial financial penalty.

The aim of this paper is to establish a framework for assessing, validating, and selecting compliance tools that will be useful to ship operators and inspectors as the regulations enter into force. The framework is comprised of three stages: (1) proof-of-concept, (2) validation and verification, and (3) feasibility and final selection. In this paper, the framework is first described. Next, a case study is presented for the first (proof-of-concept) stage, which uses variable fluorescence as an example. The case study encompasses preliminary laboratory trials, a subject matter workshop, and subsequent field trials that tested the hypotheses put forth in the workshop. Because the goal of this work is to provide a framework and preliminary data on the appropriateness of variable fluorescence as a compliance tool—not to assess individual instruments—the instruments are described in generic terms. Future work is planned to address the suitability of variable fluorescence fluorometers in the second and third stages of the framework.

2. Assessment framework

2.1. Proof-of-concept

A proof-of-concept pilot study is an opportunity to demonstrate—on a small scale and in a controlled manner—a principle or the potential and capabilities of an approach, method, or instrument. In this context, an approach is a general means to collect information on the number of living organisms, for example, measuring the chlorophyll fluorescence in a ballast water sample; a method is a detailed protocol for collecting measurements; and an instrument is a tool used to collect data in the laboratory or field (here, a ship). The use of a pilot study reduces the risk of making an inappropriate selection, since it serves as a first step in determining the feasibility (and, later, the implementation) of a new approach, method, or instrument. In the proposed framework, the proof-of-concept stage consists of laboratory experiments, a subject matter workshop (to provide expert opinion on the utility of the proposed approach), and initial field trials. Traditionally, laboratory and field experiments are conducted as new approaches, methods, and tools are explored, and both types of experiments would be served well by the input from a workshop convened of subject-matter-experts. By pooling the advice, experience, and expertise of known practitioners and leaders in the field, mistakes and potential problems can be avoided.

2.2. Verification and validation

Once the proof-of-concept pilot studies have been completed, and if the results support decisions to move forward, the validation and verification of specific approaches, methods, and instruments can take place. Here, validation ensures the tool is used as intended, whereas verification ensures specific requirements (e.g., accuracy) are sufficiently met; both processes are informed by objective data. If instruments are to be employed in compliance monitoring of ballast water discharge, then rigorous, independent validation and verification are required to quantify their individual performance parameters (under use-intended applications) and to quantify measurement error or uncertainties. In fact, existing verification and validation programs can be used as models to validate proposed ballast water compliance monitoring tools. Examples include: (1) the EPA Environmental Technology Verification (ETV) Program (EPA, 2010), in which land-based ballast water test facilities verify and validate the performance of BWMSs through large-scale testing under conditions representing coastal waters, and (2) the Alliance for Coastal Technologies (ACT), in which sensors and platforms for studying and monitoring freshwater, coastal, and ocean environments are verified and validated using field trials and laboratory tests to recreate controlled environmental conditions. Most of the following parameters are typically used in ACT testing (e.g., ACT, 2005, 2008, 2012b) and are recommended for verification and validation testing of ballast water compliance tools:

Accuracy – exactness of a measurement, which is estimated by repeated comparisons between instrument measurements and reference water samples. Accuracy can be difficult to determine