Chapter 5.   Ballast Water Exchange Experiments on Tankers

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5A. Purpose

The primary objective of this research component is to measure the efficacy of ballast water exchange in removing various types of taxa from ballast tanks of oil tankers. There are very few quantitative studies that have measured the effects of exchange, and these are restricted to just a few vessel types and measure the effect on a small subset of entrained taxa. It is likely, however, that the efficacy of exchange varies by vessel type, tank design, and organism type. To date, there have been no measures of ballast water exchange for oil tankers.

Ballast water exchange is the most widely used national and international management strategy to limit new invasions associated with ships' ballast water (Hallegraeff 1998, Zhang & Dickman 1999, Dickman and Zhang 1999,. Moreover, exchange is currently the only treatment method available for commercial ships to reduce the quantities of non-indigenous coastal plankton in ballast water (National Research Council 1996). This practice is recommended by the International Maritime Organization (IMO) to reduce the risk of invasion by shipping. Furthermore, the U.S. Congress passed the National Invasive Species Act of 1996 (NISA) to encourage ballast water exchange. Specifically, NISA requests that vessels arriving from outside of the Exclusive Economic Zone (EEZ) voluntarily conduct open-ocean exchange of ballast tanks to be discharged in U.S. ports

Commercial ships practice two basic types of ballast water exchange to replace coastal with oceanic water. Flow-Through (FT) Exchange is conducted by pumping oceanic sea water continuously through a ballast tank to flush out the ballast water originating from a coastal source port. Empty-Refill (ER) Exchange is performed by emptying a ballast tank of its coastal water and refilling it with oceanic water.

Each exchange method may vary in efficacy due to the amount and circulation of water being removed, independent of any tank- or vessel-specific effects on efficacy. For example, FT Exchange initially has the effect of dilution but not complete replacement of ballast water. Alternatively, organisms may differ in their distribution or response to water turbulence. Some taxa may swim against currents or always reside near the bottom of tanks, which could greatly influence the effect of ballast water exchange on removal.

To maximize the degree of exchange, multiple exchanges are often recommended. The current IMO standard recommendation is 300% exchange for Flow-Through, while 100-200%

exchange is common for Empty-Refill. These recommended standards provide a theoretical level of at least 90% replacement of coastal water by oceanic water, but this is largely untested among the broad range of vessel types and tank configurations. Specifically, there are almost no experimental analyses which quantify the efficacy of alternative exchange methods and multiple tank exchanges, even though (a) this is the present national and international management strategy being implemented and (b) the cost of such exchanges is substantial in ship fuel and operations time.

We initiated a rigorous quantitative comparison of ballast water exchange methods on oil tankers arriving to PWS. Across two years, we conducted replicated exchange experiments, allowing us to measure the effects of both exchange methods on reduction of entrained organisms and standard physical and biological tracers.

We hypothesize that (1) Empty-Refill exchange will have the highest efficiency, (2) relatively little reduction in density occurs after the first exchange event, and (3) a significant difference exists among taxa on the effect of ballast water exchange. Our experiments were designed to directly test these hypotheses and provide needed quantitative data on this management practice.

This work was initiated in two phases, extending the duration of the analyses and allowing us to increase the replication (and therefore strengthen the statistical power and value of this analysis). The first phase was initiated in summer of 1998. Through the cooperation and financial support from the American Petroleum Institute, SeaRiver and ARCO, we conducted the ballast water exchange experiments on four separate voyages of tankers to Alaska in June/July of that year. The second phase was initiated in spring of 1999, when we received additional funding from U.S. Fish and Wildlife Service to conduct similar experiments (with increased measurements) on another four voyages in summer. In addition to analysis of these experiments, we agreed (with additional funding from phase two) to provide a review of existing data on the efficacy of ballast water exchange, allowing us to examine our results from oil tankers to those reported for other vessel types.

All of the experiments have been completed, but we have not yet completed the full analysis of all samples. We report here on the experiments conducted, including the status of sample analysis and initial results. We will provide a comprehensive report of the results across both phases upon completion of our analyses. We anticipate that these results will be available by June 2000.

5B. Methods

Although the overall goal of this research was to measure the efficacy of ER and FT methods of ballast water exchange in removing coastal plankton from ballast water, our experimental design allowed us to address three specific objectives:

- Compare the efficacy of ER and FT exchange methods in removing a range of different materials (biotic and abiotic);
- Measure the effect of repeated exchanges: comparing 100, 200, and 300% exchange of the tanks.

- Measure the survivorship of organisms in ballast water over the course of routine voyages. Since the density of organisms can change during a voyage (see Chapter 3 for discussion), it was important to control for such changes in experimental tanks that were independent of the exchange treatment. For this purpose, we included identical measures for an unexchanged control tank on every vessel. Although key to the experimental analysis, this also provided an opportunity to address this third objective.

All experiments were conducted aboard oil tankers during regular operations, en route to Port Valdez. Each tanker served as an experimental platform. Each ship was boarded by a pair of SERC staff at a domestic source port (San Francisco, Puget Sound, or Long Beach), where ballast water used to fill the segregated ballast tanks just in advance of departure for Port Valdez. The tanks underwent various treatments and were sampled repeatedly during the voyage (below).

Experimental Design

The experiment consisted of a replicated, factorial, and paired design. On each ship, we sought to use 3 different ballast tanks that were each subjected to a different treatment: No exchange (=Control), ER Exchange, and FT Exchange. Each Treatment tank was sampled as many as 5 time points, coinciding with: initial ballast loading, 100% exchange, 200% exchange, 300% exchange, and final at arrival to PWS.

Ballast water was loaded in accordance with standard operating procedures at dockside. All exchanges occurred in open, oceanic conditions well outside the influence of coastal waters (>75 miles offshore). Exchanges of tanks were managed by ships' crews in coordination with the desired sampling schedule. For FT Exchange, sea water was pumped into the ballast tanks, causing ballast water to overflow through the top of the tanks and onto the deck. After a volume of water equal to the volume of the tank was pumped, the exchange was interrupted and samples were collected. For ER Exchange, ballast tanks were drained initially by gravity and then by pumping before refilling with sea water. The process required approximately 12 hours for each multiple of exchange.

The specific details of implementation and sampling are described below in various sections.

Biotic and Abiotic Tracers.

In addition to quantifying the effect of ballast water exchange on entrained plankton communities in the ballast tanks, we used four different types of tracers for parallel measures of efficacy. One of these (salinity of the resident water) simply involved collecting and measuring attributes of the resident water. The other three involved materials that we added directly to the ballast tanks, including: Rhodamine dye to trace the fate of the initial water; 1 um Fluorescent Microspheres that simulate passive particles such as cysts; and newly hatched *Artemia* (brine shrimp) nauplii, native to San Francisco Bay, as a living particle.

Each tracer can provide information about different components of the ballast tank environment during exchange (as indicated above). Moreover, we were interested in developing some standardized measures for comparisons across ships. Since the resident community within each ship's ballast tanks may differ considerably (see Chapter 3), the tracers could provide a common currency for comparing exchange performance among many ships in a way that is simply not possible for the entrained plankton communities.

Tracers were added to ballast tanks in a standardized way, following approval for use in these experiments by the U.S. Environmental Protection Agency. The quantity of tracer was chosen to produce desired concentrations for the specific volumes of each tank, such that anticipated dilution during exchanges would allow us to detect at least a 100-fold reduction in measurable concentrations of each tracer.

Tracers were added to at least two locations in each tank during early stages of ballast tank filling (i.e., before the tank was 25-50% full), so as to increase the opportunity for mixing throughout each tank. Rhodamie and microspheres were added directly to all tanks. In contrast, *Artemia* were initially cultured (i.e., the cysts were added to salt water and hatched in buckets in advance of boarding the ship), and the resulting organisms were used to inoculate ballast tanks.

Sample Collection.

Replicate samples were collected at 2 –3 different locations (i.e., tank access points) from each tank, for up to 5 different sampling periods (as above). Sampling procedures for the plankton community followed our established protocol for characterization of ballast water (see Chapter 3 for description); *Artemia* abundance was measured as a component of the plankton (see below). Replicate whole water samples were collected from two depths (0m and 10m), using a Niskin bottle. Whole water samples were used to measure salinity, temperature, and concentrations of dye and microspheres.

For each sampling location and period, we collected 2 replicate samples for all measures. Thus, for each tank and sampling period, we obtained at least: 4 plankton samples (2 locations x 2 samples); 8 rhodamine samples (2 locations x 2 depths x 2 samples); 8 mircosphere samples (2 locations x 2 depths x 2 samples). Temperature and salinity measures were made immediately upon all replication Niskin samples (at least 8 per tank and sampling period, as above).

Although we followed the same general sampling protocol for all voyages (in both years), we collected additional whole water samples during the 1999 experiments to measure changes in the abundance of total bacteria and ciliate protozoans. For both measures, we collected at least 8 samples per tank and sampling period (2 locations x 2 depths x 2 samples). Samples were collected from all experiments in 1999 to measure total bacteria. However, we only included samples from one vessel for the protozoans, due to the time-intensive nature of analysis for this group.

Sample processing.

Water temperature and salinity were measured immediately, using a hand-held thermometer and refractometer, respectively. Plankton/*Artemia* samples were examined aboard ship initially to assess general condition (live/dead, active, lethargic) soon after collection, using dissecting microscopes; these samples were then preserved in 5% buffered formalin. The preserved plankton samples were sorted and enumerated in the laboratory as described in Chapter 3 for Fine

Analysis. Thus, densities were estimated for each taxon, and voucher samples were sent to experts to verify the taxonomic identity.

The tracers in whole water samples are being quantified in the laboratory at SERC (dye concentration with a fluorometer, micro-spheres with direct counts under a fluorescent compound microscope). Total bacteria are also being estimated by direct count with a compound microscope, using standard techniques. The protozoan have been sent to a colleague (Dr. Richard Pierce, expert in ciliate protozoa) for direct counts by taxon.

5C. Results

The experiments were conducted on 8 different voyages, which were divided evenly between the two years (Table 5.1). All experiments were conducted from June to mid July, to control for seasonal variation and to occur during a period of high plankton abundance (see Chapter 3). Six of the 8 ships included all three treatments: ER exchange, FT exchange, and control. These were SeaRiver ships, departing from the ports of San Francisco Bay and Puget Sound. However, the large ARCO tankers were not able to perform ER exchange; experiments aboard these remaining 2 ships included only FT exchange and control tanks.

Table 5.1. Overview and status of ballast water exchange experiments conducted aboard oil tankers arriving to Port Valdez, 1998-1999. For each of 8 replicate experiments: (A) The upper table indicates the vessel, start date, source port, exchange methods, and number collected samples (physical/chemical and biological); (B) The lower table indicates the status of the respective samples. Physical/chemical tracers include salinity, rhodamine, and flourescent microspheres (shown in lower table). Biological tracers include resident zooplankton and brine shrimp (Artemia) in both years, as well as total bacteria in1999 only. . Source ports: Puget Sound, WA (PS); San Francisco Bay, CA (SF); Long Beach, CA (LB). Exchange types: Empty-Refill (ER) and Flow-Through (FT). See text for experimental design.

A.

Ship	Date	Port Source	Exchange type(s)	# of samples Physical tracers	# of samples Biol. Tracers
S/R Baytown	27-Jun-98	SF	ER+FT	120	60
S/R Benicia	01-Jul-98	SF	ER+FT	120	60
S/R Long Beach	08-Jul-98	SF	ER+FT	120	60
ARCO Independence	18-Jul-98	LB	FT	80	40
S/R Baytown	11-Jun-99	PS	ER+FT	60	144
ARCO Spirit	12-Jun-99	LB	FT	64	164
S/R Baytown	08-Jul-99	PS	ER+FT	60	144
S/R Long Beach	19-Jul-99	SF	ER+FT	120	252

B.

		status of proccessing (ip=in progress)				
Ship	Date	Salinity	Rhodamine	Microspheres	Zooplankton/Artemia	Bacteria
S/R Baytown	27-Jun-98	done	done	ip	done	-
S/R Benicia	01-Jul-98	done	done	done	done	-
S/R Long Beach	08-Jul-98	done	done	done	done	-
ARCO Independence	18-Jul-98	done	done	done	done	-
S/R Baytown	11-Jun-99	ip	done	done	done	ip
ARCO Spirit	12-Jun-99	ip	done	done	done	ip
S/R Baytown	08-Jul-99	ip	done	done	ip	ip
S/R Long Beach	19-Jul-99	ip	done	done	ip	ip

We distributed our experiments among the three source ports to maximize the range of conditions (e.g., taxonomic groups, voyage duration, vessel types, and salinity), allowing us to test for general patterns among oil tankers. For example, diversity (and salinity) was generally greatest for ships from Long Beach and Puget Sound, and voyage duration differed among source ports (see Chapters 2 and 3). However, the traffic from each source port presented some unique constraints to the overall design:

(1) Ships from Long Beach could not perform ER Exchange;
(2) Ships from San Francisco contained low salinity waters, especially during the 1998 El Nino year, creating a possible physiological stress for organisms when exposed to exchange (not present at the other ports);
(3) Ships from Puget Sound were not able to complete as many exchanges during the short voyage duration, limiting the total exchange volume to 100% or 200% (instead of the 300% possible for the longer voyages from other source ports).

For all experiments on all 8 vessels, we have measured the effect of at least one full (100%) exchange for the exchange methods and tracers indicated in Table 5.1. In addition, for the majority of vessels we have also measured the effect of multiple exchange events.

Table 5.1 also indicates the number of samples taken for each voyage and the status of these samples. The analysis for physical tracers is actually twice the number shown, as the same sample is used for analysis of rhodamine and microspheres.

Although the samples are now at various stages of analysis (Table 5.1), our initial analyses suggest a significant difference between ER and FT exchange in the reduction of rhodamine dye. For example, Figure 5.1 shows the average change in concentration of rhodamine for the respective treatments across multiple exchange events in 1998. The concentration of dye was reduced by 80 and 99% (for FT and ER exchange, respectively) compared to the initial concentrations. Interestingly, the concentration of dye in the control tank increased between the first and second measures, and this change is attributed to inadequate mixing at time T_o for some ships (as evidenced by vertical stratification that was present in our raw data). Similar patterns exist for the rhodamine data collected in 1999.

Despite the rhodamine results, demonstrating relatively high levels of exchange, it is premature to draw conclusions about the efficacy of exchange to remove organisms. We are now analyzing the samples to measure removal rates for both biological and physical tracers (i.e., microspheres), and we expect to complete these analyses by June 2000. At present, it is evident that some taxa declined in abundance (following exchange) to the same extent as rhodamine dye. Figure 5.2 shows a decline in the abundance of *Limnoithona* sp. for both ER and FT exchange on one vessel. The density actually increased in the control tank, and this was due most likely to growth of copepodite stages instead of mixing. Changes in the abundance of other taxa appear to be much less striking, although analysis of the overall pattern (including variation among taxa) must await completion of all quantitative counts and taxonomic verification.

Figure 5.1. Effect of ballast water exchange on rhodamine dye concentrations. Data are from exchange experiments conducted in the ballast tanks of oil tankers arriving to Port Valdez. Shown for 1998 voyages (n=4 vessels) is the mean percent change in rhodamine dye concentration (compared to the initial time measure) at each of four successive time points for 3 different treatments: Control – ballast tanks that did not undergo exchange; ER Exchange – ballast tanks that underwent Empty-Refill Exchange; FT Exchange – ballast tanks that underwent Flow-Through Exchange. See text for experimental design.

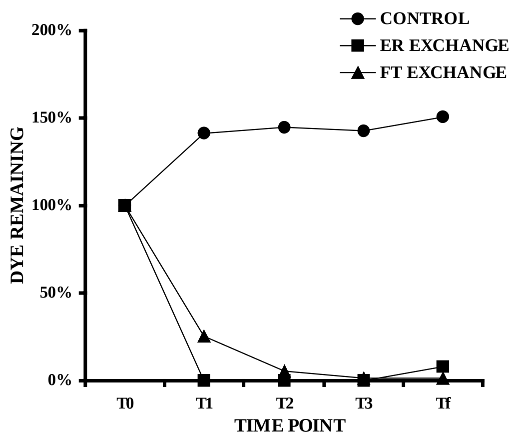
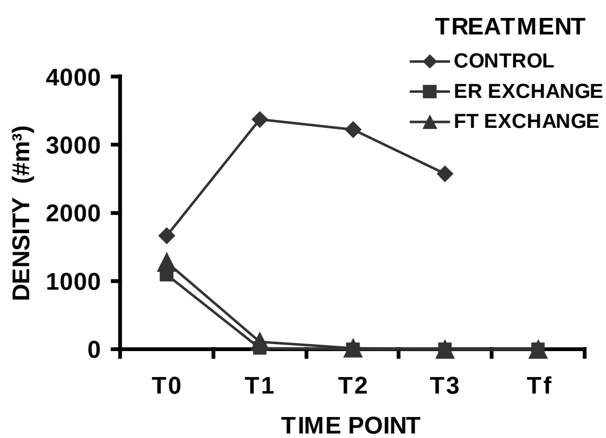


Figure 5.2. Effect of ballast water exchange on Limnoithona sp.density. Data are from exchange experiments conducted in the ballast tanks of an oil tanker arriving to Port Valdez. Shown for one voyage is the mean density of the copepod SPECIES at each of five successive time points for 3 different treatments: Control – ballast tanks that did not undergo exchange; ER Exchange – ballast tanks that underwent Empty-Refill Exchange; FT Exchange – ballast tanks that underwent Flow-Through Exchange. See text for experimental design.



Changes in the density of entrained biota within the control tanks of each vessel will measure survivorship over time (i.e., during transit). This will allow us to test our hypothesis (above) about the effect of voyage duration on survivorship, and whether differences among port sources are due to such time-dependent survivorship.

5D. Discussion

This is the first study to compare the relative efficiency of exchange methods (ER and FT exchange) for any vessel type or taxon.

Quantitative and experimental analyses of ballast water exchange have been very limited to date, and these can be classified into 3 general types:

1. **Comparison of ballast water in ships that have or have not exchanged ballast water.** These data indicate that, compared to ships that have not conducted mid-ocean ballast water exchange, ships with exchanged ballast water have reduced abundance of plankton. However, with this approach, it is not possible to (a) compare directly methods of exchange (FT vs. ER) , (b) control for initial plankton densities or the percentage of water exchanged (as below). Thus, the data are highly variable and interpretation is limited (e.g., Smith et al. 1996).

2. **Comparison of ballast water in tanks of the same ship that have not exchanged ballast water, with measurements made only after exchange is complete and upon arrival to port.** These data suggest a reduction of roughly 90% occurred, but interpretation is also limited with this design (Ruiz and Hines 1997; see below). Initial variation among tanks can be considerable, depending upon the timing (e.g., day vs. night) and sequence of ballasting, which creates potentially large differences among tanks independent of exchange treatment. Furthermore, it is not possible to compare efficiency between methods of exchange, or for multiples of exchange, because ships usually only perform one method and volume of exchange.

3. **Comparison of ballast water in tanks of the same ship before and after exchange of ballast water, with measurements made on board ship at various stages of the exchange process.** These data provide a clear measure of efficiency within a single tank, and we have conducted this analysis on approximately 5 military vessels and 1 commercial bulk carrier (Ruiz et al. 1999, Wohnam et al. 1996). However, the sample size is small (and taxa included in ships to date are limited), and comparison between exchange methods or multiples of exchange (on the same ship) has not been included or possible to date.

The 1997 Pilot Study provided initial data comparing the end result of FT Exchange (300% and 100%) on plankton abundance. These data suggested that approximately 70- 90% of coastal plankton was removed by FT exchange, compared to control tanks from the same source. Interestingly, it was not clear that an increased level of exchange (100 vs. 300 %) produced a parallel reduction in key taxonomic groups.

In both the Pilot Study and the current study (Chapter 3), it was evident that abundance of coastal organisms was 10-100 fold lower in tankers from foreign ports (that underwent ballast water exchange) compared to domestic arrivals (that do not undergo exchange). Although this difference may result from the exchange, it is confounded by differences in the initial concentrations (i.e., source ports) and voyage duration that can also have a strong influence.

The results of this study – the most comprehensive and rigorous to date - will significantly advance our understanding of the strengths and limitations of ballast water exchange, providing multiple quantitative measures for the two exchange methods, both for oil tankers specifically but for commercial ships more generally.

Importantly, when completed, our study will also provide a set of standards for evaluating ballast water management in two ways. First, we have developed and tested a standard set of assays to measure exchange efficiency across vessel types, vessel tanks, and under various conditions. This will be useful in comparing efficiency among studies. Second, the results obtained by this and future studies will provide a benchmark against which to assess the efficacy of emerging technologies.

5E. References

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