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DELTA STEWARDSHIP COUNCIL

SHORE-BASED BALLAST WATER TREATMENT IN CALIFORNIA  
**TASK 5: ASSESSMENT OF TREATMENT TECHNOLOGIES**

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Table of Contents

**Executive Summary ..... 1**

    1.1 Task 5 Scope ..... 1

    1.2 Summary of Findings ..... 1

**Section 2 Background ..... 5**

    2.1 Ballast Water Pollutants ..... 5

    2.2 Treatment Standards ..... 5

    2.3 Current Ballast Water Treatment Approach ..... 6

**Section 3 On-shore Treatment Technologies ..... 8**

    3.1 Physical Separation Processes ..... 8

        3.1.1 Coagulation, Flocculation, and Sedimentation ..... 8

        3.1.2 Filtration ..... 10

        3.1.3 Mechanical Treatment Summary ..... 13

    3.2 Physical Treatment ..... 14

        3.2.1 Ultraviolet ..... 14

    3.3 Chemical Treatment ..... 17

        3.3.1 Ozone ..... 17

        3.3.2 Chlorine – Sodium hypochlorite ..... 19

        3.3.3 Electrochlorination ..... 20

        3.3.4 Chemical Treatment Summary ..... 22

**Section 4 Further Considerations ..... 24**

    4.1 California’s Interim Ballast Water Discharge Performance Standards ..... 24

    4.2 Disinfection Byproducts ..... 25

    4.3 Compliance Monitoring ..... 26

    4.4 Residuals Management ..... 28

    4.5 Ballast Water Treatment at a Municipal Treatment Plant – Stockton Mass Balance .28

        4.5.1 Background ..... 28

        4.5.2 Blending Analysis ..... 28

**Appendix A Study Overview and Definitions ..... A-1**

    Study Overview ..... A-2

    Tasks Overview ..... A-2

    Case Studies Overview ..... A-3

    Definitions ..... A-4

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# References

1. Abbadi, J. Saleh, R., Nusseibeh, S., Qurie, M., Khamis, M., Karaman, R., Scrano, L., Aurelio Bufo, S., 2012. Microbial Removal from Secondary Treated Wastewater Using a Hybrid System of Ultrafiltration and Reverse Osmosis. *Journal of Environmental Science and Engineering*, pp. 853-869
2. ABS, 2011. Ballast Water Treatment Advisory.
3. American Water Works Association. 2015. On-site Generation of Hypochlorite. *Manual of Water Supply Practices—M65*. American Water Works Association: Denver, CO.
4. AwwaRF. 2001. Evaluation of Dynamic Energy Consumption of Advanced Water and Wastewater Treatment Technologies. American Water Works Association Research Foundation, ISBN 978-1-60573-033-2.
5. AwwaRF. 2005. Integrating UV Disinfection into Existing Water Treatment Plants. American Water Works Association Research Foundation, ISBN 1-58321-401-1.
6. Balaji, R., Yaakob, O., Koh, K. 2014. A Review of Developments in Ballast Water Management. *Environmental Reviews*, 22, pp. 1-13.
7. Black and Veatch. 2010. “White’s Handbook of Chlorination and Alternative Disinfectants”. John Wiley & Sons, Inc.: Hoboken, NJ.
8. Casson, L.W., Bess, J.W., 2003. Conversion to On-site Sodium Hypochlorite Generation: Water and Wastewater Applications. CRC Press: Boca Raton, FL.
9. Cooper, W.J., Cordell, J.R., Dethloff, G.M., Dinnel, P.A., Gensemer, R.W., Herwig, R.P., House, M.L., Kopp, J.A., Mueller, R.A., Perrins, J.C. and Ruiz, G.M. 2002. Full-Scale Ozone Ballast Water Treatment for Removal of Marine Invasive Species. University of North Carolina, Department of Chemistry and Center for Marine Science.
10. Dang, K., Yin, P., Sun, P., Xiao, J. and Song, Y. 2003. Application Study of Ballast Water Treatment by Electrolyzing Seawate., In Second International Symposium on Ballast Water Treatment. International Maritime Organization, London.
11. Delacroix, S., Vogelsang, C., Tobiesen, A. and Liltved, H. 2013. Disinfection By-Products and Ecotoxicity of Ballast Water after Oxidative Treatment—Results and Experiences from Seven Years of Full-Scale Testing of Ballast Water Management Systems. *Marine Pollution Bulletin*, 73(1), pp.24-36.
12. Drake, L., Doblin, M., Dobbs, F. 2007. Potential Microbial Bioinvasions via Ships’ Ballast Water, Sediment, and Biofilm. *Marine Pollutant Bulletin*, 55 (1), pp. 333-341.
13. EPA. 2006. Ultraviolet Disinfection Guidance Manual for the Final Long Term 2 Enhanced Surface Water Treatment Rule. United States Environmental Protection Agency Office of Water, EPA 815-R-06-0007.
14. EPA Water Treatment Manual. 2011. Water Treatment Manual Disinfection. Environmental Protection Agency (Ireland) Office of Environmental Enforcement, ISBN
15. Garland Science. 2011. “Microbes in the Marine Environment”. Taylor and Francis Group. New York, NY.

16. Guastalli, A., Simon, F., Penru, Y., de Kerchove, A., Llorens, J., Baig, S. 2013. Comparison of DMF and UF Pretreatments for Particulate Material and Dissolved Organic Matter Removal in SWRO Desalination. *Desalination*, 332, pp. 144-150.
17. Gregg, M., Rigby, G. and Hallegraeff, G.M. 2009. Review of two decades of progress in the development of management options for reducing or eradicating phytoplankton, zooplankton and bacteria in ship's ballast water. *Aquatic Invasions*, 4(3), pp.521-565.
18. Herwig, R.P., Cordell, J.R., Perrins, J.C., Dinnel, P.A., Gensemer, R.W., Stubblefield, W.A., Ruiz, G.M., Kopp, J.A., House, M.L. and Cooper, W.J. 2006. Ozone Treatment of Ballast Water on the Oil Tanker S/T Tonsina: Chemistry, Biology and Toxicity. *Marine Ecology Progress Series*, 324, pp.37-55.
19. Kazumi, J. 2007. Ballast Water Treatment Technologies and Their Application for Vessels Entering the Great Lakes via the St. Lawrence Seaway. Prepared for Committee on the St. Lawrence Seaway: Options to Eliminate Introduction of Nonindigenous Species into the Great Lakes, Phase 2 Transportation Research Board and Division on Earth and Life Studies.
20. Langlais, B., Reckjow, D.A., Brink, D.R. (eds) 1991. "Ozone in Water Treatment: Applications and Engineering". CRC Press: Boca Raton, FL.
21. Lau, W.J, Goh, P.S., Ismail, A.F., Lai, S.O. 2013. Ultrafiltration as a Pretreatment for Seawater Desalination: A Review. *Membrane Water Treatment*, 5 (1), pp 15-29.
22. Lee II, H., Reusser, D.A., Frazier, M., and Ruiz, G. 2010. Density Matters: Review of Approaches to Setting Organism-Based Ballast Water Discharge Standards. Environmental Protection Agency Office of Research and Development, National Health and Environmental Effects Research Laboratory, Western Ecology Division, EPA/600/R-10/031.
23. Liberti, L., Notarnicola, M., Petruzzelli, D. 2003. Advanced Treatment for Municipal Wastewater Reuse in Agriculture. *UV Disinfection: Parasite Removal and By-Product Formation*. *Desalination*, 152, pp 315-324.
24. Liltved, H., Vogelsang, C., Modahl, I. and Dannevig, B.H.. 2006. High Resistance of Fish Pathogenic Viruses to UV Irradiation and Ozonated Seawater. *Aquacultural Engineering*, 34(2), pp.72-82.
25. NYSERDA. 2004. Evaluation of Ultraviolet (UV) Radiation Disinfection Technologies for Wastewater Treatment Plant Effluent. Prepared for New York State Energy Research and Development Authority.
26. Matin, A., Khan, Z., Zaidi, S.M.J., Boyce, M.C. 2011. Biofouling in Reverse Osmosis Membranes for Seawater Desalination: Phenomena and Prevention. *Desalination*, 281, pp. 1-16.
27. Matousek, R.C., Hill, D.W., Herwig, R.P., Cordell, J.R., Nielsen, B.C., Ferm, N.C., Lawrence, D.J. and Perrins, J.C. 2006. Electrolytic Sodium Hypochlorite System for Treatment of Ballast Water. *Journal of Ship Production*, 22(3), pp.160-171.
28. McCarthy, S., Khambaty, F. 1994. Internal Dissemination of Epidemic *Vibrio Cholerae* by Cargo Ship Ballast and Other Nonpotable Waters. *Applied and Environmental Microbiology*, pp. 2597-2601.
29. Macdonald, E., Davidson, R. 1997. Ballast Water Project Final Report. Prepared for Scottish Office of Agriculture, Environmental and Fisheries Department.

30. Oemcke, D., van Leeuwen, J. 2003. Chemical and Physical Characterization of Ballast Water Part 1: Effects on Ballast Water Treatment Processes. *Journal of Marine Environmental Engineering*, 7, pp. 47-64.
31. Oemcke, D., and Leeuwen, J.H.V. 2004. Seawater Ozonation of *Bacillus Subtilis* Spores: Implications for the Use of Ozone in Ballast Water Treatment. *Ozone: Science & Engineering*, 26(4), pp.389-401.
32. Ottoey Olson, R., Hoffmann, F., Hess-Erga, O., Larsen, A., Thuestad, G., Alne Hoell, Ingunn. 2015. Ultraviolet Radiation as Ballast Water Treatment Strategy: Inactivation of Phytoplankton Measured with Flow Cytometry. *Marine Pollutant Bulletin*, In Press.
33. Perrins, J.C., Cooper, W.J., Van Leeuwen, J.H. and Herwig, R.P. 2006. Ozonation of seawater from different locations: formation and decay of total residual oxidant—implications for ballast water treatment. *Marine Pollution Bulletin*, 52(9), pp.1023-1033.
34. SAB. 2011. U.S. Environmental Protection Agency Science Advisory Board Ecological Processes and Effects Committee Augmented for the Ballast Water Advisory (Ballast Water Advisory Panel).
35. Sassi, J. and Rytönen, J, 2005. Experiments with Ultraviolet Light, Ultrasound and Ozone Technologies for Onboard Ballast Water Treatment. VTT Technical Research Center of Finland. Vuorimiehentie, Finland.
36. Schäfer, A.I., Fane A.G., Waite, T.D. 2001. Cost Factors and Chemical Pretreatment in the Membrane Filtration of Waters Containing Natural Organic Matter. *Water Research*, 35(6), pp. 1509-1517
37. Stocks, D.T., O'Reilly, M. and McCracken, W. 2004. Sodium hypochlorite as a ballast water biocide. In *Second International Symposium on Ballast Water Treatment*. International Maritime Organization, London (pp. 80-87).
38. Valavala, R., Sohn, J., Han, J., Her, N., Yoon, Y. 2011. Pretreatment in Reverse Osmosis Seawater Desalination: A Short Review. *Environmental Engineering Research*, 16 (4), pp. 205-212.
39. Voutchkov, N. 2010. Considerations for Selection of Seawater Filtration Pretreatment System. *Desalination*, 261, pp. 354-364.
40. Voutchkov, N. 2013. "Desalination Engineering Planning and Design". McGraw-Hill Companies, Inc., NY, NY.
41. Water Treatment. 2005. *Water Treatment Principles and Design*. MWH, ISBN 0 471 11018 3.
42. WERF. 2005. *Operation of Municipal Wastewater Treatment Plants – Chemical Storage and Handling*. Water Environment Federation.
43. WHO. 2004. *Safe Piped Water: Managing Microbial Water Quality in Piped Distribution Systems*. Published on behalf of the World Health Organization by IWA Publishing.
44. Yang, H., Kim, H. 2009. Effect of Coagulation on MF/UF for Removal of Particles as a Pretreatment in Seawater Desalination. *Desalination*, 249, pp. 45-52.
45. Zhang, S., Chen, X., Yang, D., Gong, W., Wang, Q., Xiao, J., Zhang, H. and Wang, Q. 2003. Effects of the chlorination treatment for ballast water. In *Second International Symposium on Ballast Water Treatment*. International Maritime Organization, London.

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# Executive Summary

This report is part of an overall coordinated study evaluating the feasibility of using shore-based mobile or permanent ballast water treatment facilities to meet California's Interim Ballast Water Discharge Performance Standards (CA Interim Standards). Tasks 2 through 5 are submitted together to discuss the practical necessities for shore-based treatment system implementation, from the modifications onboard vessels through to the treatment technologies used in the facilities.

The main objective of this Task 5 report is to determine the efficacy of a combination of on-shore ballast water treatment technologies (physical, mechanical, and chemical) to remove/inactivate microorganisms below the stringent concentrations set forth in the CA Interim Standards.

This report identifies standardized treatment approaches which may be able to achieve the CA Interim Standards, though it is noted that additional bench-scale and in-field testing would be required to verify the validity, performance, and reliability of the treatment approaches described.

## 1.1 Task 5 Scope

The scope of this task is to assess all potential types of treatment technologies available for shore-based reception facilities that can meet California's interim performance standards and how the efficacy of such systems can be measured. Work completed as part of this task includes:

- Description of the technology and its current state of development,
- Summary of any testing performed relative to ballast water treatment,
- Discussion of potential efficacy relevant to the CA Interim Standards,
- Methods for determining compliance of the effluent with the standard.

## 1.2 Summary of Findings

There were three physical (coagulation/flocculation/sedimentation, dual-media filtration, and membrane filtration), one mechanical (UV disinfection), and three chemical (ozone disinfection, sodium hypochlorite disinfection, and electrochlorination disinfection) ballast water treatment technologies studied in this report for on-shore ballast water treatment. The efficacy of each technology and combination of technologies to meet the CA Interim Standards was determined primarily using estimated log zooplankton (microorganisms  $> 50 \mu\text{m}$ ), protists ( $50 \mu\text{m} \geq$  microorganism  $> 10 \mu\text{m}$ ), bacteria and virus removals. It was estimated 5-log removal of zooplankton, protists, and bacteria and 7-log removal of viruses would be required to meet the CA Interim Standards.

It was determined the most effective treatment trains for ballast water treatment were coagulation, flocculation, and sedimentation followed by membrane filtration and UV or chemical disinfection. The microorganism removal for the individual treatment processes and treatment trains are summarized in Table 1.

Coagulation, flocculation, and sedimentation offer negligible microorganism removal; however, they were included because they improve microorganism removal by dual-media and membrane filtration and provide a means to manage residual waste streams produced during filter backwashes. There is little information on the removal of zooplankton and protists by dual-media membrane filtration; however, 5-log removal by both technologies was assumed in this study due to the large size of zooplankton and protists compared to the size of particles removed in dual-

media and membrane filtration but this would need to be confirmed through field test. Membrane filtration was given credit 3-log bacteria removal as demonstrated by Guastalli et al. (Guastalli et al., 2013); membrane filtration was not given credit viruses removal. Based on the available literature, it was found the treatment trains including UV and chemical disinfection can achieve the required bacteria removal (5-log) but do not achieve the required virus removal (7-log).

The lower virus removals, 2- and 4-log for UV disinfection were reported for UV doses of 100 and 190 mJ/cm<sup>2</sup>. The UV log virus inactivation has a linear relationship with the UV dose (EPA, 2006), which is a function of the UV lamp irradiance intensity and contact time. The EPA (EPA, 2006) provides tables summarizing UV dose requirements to achieve specific log virus inactivation. These UV doses are related to fresh water but should be applicable to ballast water because UV disinfection is not particularly affected by salinity, pH, or other water quality parameters not related to organic matter or suspended solids. By extrapolating from the EPA UV dose requirement table, the estimated minimum required dose to achieve 7-log virus removal would be 310 mJ/cm<sup>2</sup>.

**Table 1 Removal of regulated ballast water contaminants by proposed treatment steps and treatment trains**

Physical Treatment		Mech./Chem. Treatment	Total System Removal
<b>Coag./Floc./Sed.</b> <b>Removal:</b> Org. > 50 µm = Low 50 ≥ Org. > 10 = Low Bacteria = Negligible Virus = Negligible	<b>Membrane Filtration</b> <b>Removal:</b> Org. > 50 µm = 5-log 50 ≥ Org. > 10 = 5-log Bacteria = 3-log Virus = Negligible	<b>UV Disinfection</b> <b>Removal:</b> Org. > 50 µm ≈ Low 50 ≥ Org. > 10 ≈ Low Bacteria = 2-log <sup>[1]</sup> Virus = 2-log, 4-log <sup>[2]</sup>	<b>Treatment Train:</b> <b>Coag./Membrane/UV</b> Org. > 50 µm = <b>5-log</b> 50 ≥ Org. > 10 = <b>5-log</b> . Bacteria = > <b>5-log</b> <sup>[1]</sup> Virus = <b>2-log, 4-log</b> <sup>[2]</sup>
		<b>Chemical Disinfection</b> <b>Removal:</b> Org. > 50 µm ≈ Low 50 ≥ Org. > 10 ≈ Low Bacteria = > 4-log <sup>[3]</sup> Virus = 1-log <sup>[4]</sup>	<b>Treatment Train:</b> <b>Coag./Membrane/Chem.</b> Org. > 50 µm = <b>5-log</b> 50 ≥ Org. > 10 = <b>5-log</b> Bacteria = > <b>7-log</b> <sup>[3]</sup> Virus = <b>1-log</b> <sup>[4]</sup>

[1] Removal achieved at a UV dose of 60 mJ/cm<sup>2</sup>

[2] 2-log and 4-log removal based on UV doses of 100 and 190 mJ/cm<sup>2</sup>

[3] Removal based on a TRO ≥ 5 mg/L and HRT ≥ 10 hours

[4] Removal based on a TRO = 8.1 mg/L and HRT = 4 minutes

Similar to UV disinfection, virus removal for chemical disinfection can be improved by increasing the dose. A common way to calculate the chemical disinfection dose is to multiply the chemical concentration at the end of treatment by the treatment time – this is referred to as Ct. The Ct used by Liltved et al. (Liltved et al. 2006) used to achieve 1-log virus removal presented was approximately 32 mg-min/L. This Ct is almost 100 times lower than the Ct used to achieve the 4-log bacteria removal (Ct = 3,000 mg-min/L). Increasing the Ct by two orders of magnitude will definitely increase the virus removal but testing of the ballast water would be required to determine if a Ct = 3,000 mg-min/L is sufficient or if a higher Ct is required. Although more testing is required, it is likely 7-log virus removal should be achievable using UV and chemical disinfection at higher doses than have previously been tested.



The treatment technology selection for the different ports was based on the removal efficiency and on the system footprint and capital costs. The available space at a few of the ports is limited; additionally, the treatment system needed to fit on a truck-based system at Port Hueneme and on a barge based system at the Port of El Segundo. To aid in this decision making, the capital cost and footprint, as well as energy demand, chemical cost, and other design parameters, were determined as a function of the ballast water flow. A summary of the compiled design parameters is provided in Table 2. The implementation of these design parameters for the ports being evaluated for on-shore ballast water treatment is presented in the Task 4 report.

**Table 2 Summary of treatment process design parameters and cost and footprint estimates**

PHYSICAL TREATMENT		
Coagulation, Flocculation, and Sedimentation		
Parameter	Units	Value
Capital Cost <sup>[1, 2]</sup>	\$	= 24 (Q) + 75,000 <sup>[3]</sup>
Chemical Cost	\$/dry ton	485
Chemical Dose	mg/L	20
HRT <sup>[4]</sup> , Floc Basin	minutes	10 – 40
Depth, Floc Basin	m (ft)	3.5 – 4.5 (11.5 – 14.8)
HRT, Settler <sup>[5]</sup>	minutes	10 – 20
Depth, Sedimentation	m (ft)	3.4 – 5 (11.5 – 16.4)
Sludge Production	lbs ferric chloride/mgd	= [(Dose)(0.66)(8.34)] + [(Turbidity)(1.3)(8.34)]
Dual-Media Gravity Filtration		
Filtration Rate	m <sup>3</sup> /m <sup>2</sup> -h (gal/ft <sup>2</sup> -min)	8 – 15 (3 – 6)
Water Recovery	%	94 – 98
Capital Cost <sup>[2]</sup>	\$	= 64 (Q) + 380,000 <sup>[3]</sup>
Footprint	m <sup>2</sup> /1000 m <sup>3</sup> -day (ft <sup>2</sup> /mgd)	30 – 50 (1,200 – 2,100)
Energy Demand	kWh/m <sup>3</sup> (kWh/1000 gal)	0.05 (0.2)
Membrane Filtration		
Flux	L/m <sup>2</sup> -hr (gal/ft <sup>2</sup> -day)	40 – 80 (24 – 47)
Water Recovery	%	88 – 94
Capital Cost <sup>[2]</sup>	\$	Lower Limit = 59 (Q) + 830,000 <sup>[3]</sup> Upper Limit = 105 (Q) + 1,000,000 <sup>[3]</sup>
Footprint	m <sup>2</sup> /1000 m <sup>3</sup> -day (ft <sup>2</sup> /mgd)	20 – 35 (840 – 1,500)
Energy Demand	kWh/m <sup>3</sup> (kWh/1000 gal)	0.2 – 0.4 (0.75 – 1.5)
MECHANICAL TREATMENT		
Ultraviolet Disinfection		
Parameter	Units	Value
Equipment Cost <sup>[6]</sup>	\$	= 13 (Q) + 96,000 <sup>[3]</sup>
Footprint	ft <sup>2</sup>	Q < 17 mgd = 84 (Q) + 350 <sup>[3]</sup> Q > 17 mgd = 40 (Q) + 1220 <sup>[3]</sup>
Energy Demand	kWh/m <sup>3</sup> (kWh/1000 gal)	0.2 (0.8)
CHEMICAL TREATMENT		
Ozone Disinfection		
Parameter	Units	Value
Equipment Cost <sup>t[7]</sup>	\$/1000 m <sup>3</sup> (\$/mgd)	65,000 (245,500)
Energy Demand	kWh/kg (kWh/lb)	22 – 26 (10 – 12)

Chemical Dose <sup>[8]</sup>	mg/L-h	0.7 – 1.3
HRT <sup>[4]</sup>	hours	10
<b>Chlorine – Sodium Hypochlorite Disinfection</b>		
Equipment Cost <sup>[9]</sup>	million \$	= 0.006 (L) + 0.27 <sup>[10]</sup>
Chemical Cost <sup>[9, 11]</sup>	\$/m <sup>3</sup> (\$/gal)	160 – 264 (0.6 – 1.0)
Chemical Dose <sup>[12]</sup>	mg/L	20
HRT <sup>[4]</sup>	hours	24
<b>Electrochlorination Disinfection</b>		
Equipment Cost <sup>[9]</sup>	million \$	= 0.0011 (L) + 4.0 <sup>[10]</sup>
Energy Demand	kWh/kg (kWh/lb)	4 (1.8)
Chemical Dose <sup>[13]</sup>	mg/L	15
HRT <sup>[4]</sup>	hours	12

[1] Capital cost is only for high-rate plate settler

[2] Capital cost calculation is in 2013 dollars

[3] Flow (Q) is in m<sup>3</sup>/day

[4] Hydraulic retention time (HRT)

[5] Detention is for high-rate plate settler

[6] Capital cost calculation is in 2004 dollars

[7] Equipment cost estimate is in 1999 dollars

[8] Chemical dose estimated assuming a 10-h retention time and 4-log bacteria removal

[9] Capital cost estimate is in 2015 dollars

[10] Load (L) = flow rate x chlorine dose x 8.34. The units for the flow rate is million gallons per day (MGD) and the units for the chlorine dose is in mg/L.

[11] Chemical cost is estimated for a 12.5% sodium hypochlorite solution

[12] Chemical dose estimated assuming a 24-h retention time

[13] Chemical dose estimated assuming a 12-h retention time

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## Section 2 Background

### 2.1 Ballast Water Pollutants

Ballast water discharges are a major pathway for the introduction of nonindigenous invasive species (including macroorganisms, microorganisms, and viruses) to domestic marine, estuarine, and freshwater ecosystems. Aside from invasive species, ballast water contains suspended solids, organic material, and other contaminants which can reduce the efficacy of potential ballast water treatment technologies. Reported concentrations of microorganisms, viruses, and other contaminants contained in ballast water are summarized in Table 3.

**Table 3 List of ballast water pollutants**

Microorganisms	
Fecal Coliform, CFU <sup>1</sup> per 100 mL	3.0 – 510 <sup>[2]</sup>
Bacteria, per 100 mL	8.0 x 10 <sup>8</sup> <sup>[3]</sup>
Virus, per 100 mL	1.4 x 10 <sup>11</sup> <sup>[3]</sup>
<b>General Water Chemistry</b>	
pH	7.0 – 8.6 <sup>[4]</sup>
Salinity, %	23 – 33 <sup>[4]</sup>
Alkalinity, mg/L-CaCO <sub>3</sub>	29 – 140 <sup>[4]</sup>
Turbidity, NTU	0.7 – 52 <sup>[4]</sup>
Total Suspended Solids (TSS), mg/L	1.7 – 26 <sup>[4]</sup>
Transmittance, % (254)	55 – 100 <sup>[4]</sup>
Dissolved Oxygen, mg/L	6.3 <sup>[4]</sup>
Redox Potential, mV	(-)360 – (-)60 <sup>[4]</sup>
<b>Carbon and Nutrients</b>	
Total Organic Carbon (TOC), mg/L	0.9 – 8.8 <sup>[4]</sup>
Dissolved Organic Carbon (DOC), mg/L	0.8 – 2.8 <sup>[4]</sup>
Phosphate (PO <sub>4</sub> ), mg/L	0.13 <sup>[5]</sup>
Nitrate (NO <sub>3</sub> ), mg/L	2.5 <sup>[5]</sup>
Ammonia (NH <sub>3</sub> ), mg/L	0.09 <sup>[5]</sup>

[1] Colony forming units (CFU)

[2] Drake et al., 2007

[3] McCarthy and Khambaty, 1994

[4] Oemcke and van Leeuwen, 2003

[5] Macdonald and Davidson, 1997

### 2.2 Treatment Standards

Various organizations have developed ballast water discharge standards to reduce the introduction of invasive species to new aquatic ecosystems. The International Maritime Organization (IMO) Ballast Convention of 2004 established ballast water treatment standards to limit the number of organisms allowed in ballast water discharge. The United States Coast Guard (USCG) adopted the IMO limits as part of the USCG Phase 1 Standard. California has proposed California Interim and California Final ballast water discharge standards. A summary of the USCG Phase 1 and California standards is provided in Table 4.

**Table 4 List of interim California ballast water discharge limits**

Organism Class	USCG Phase 1 Standards	CA Interim Standards	California Final Standards
Organisms > 50 µm	< 10 per m <sup>3</sup>	No detectable living organisms	No detectable living organisms
50 µm ≥ Organisms > 10 µm	< 10 per mL	≤ 1 per 100 mL	No detectable living organisms
Organisms ≤ 10 µm	No standard	Bacteria < 10 <sup>3</sup> per 100 mL Virus < 10 <sup>4</sup> per 100 mL	No detectable living organisms
<i>Escherichia coli</i>	< 250 CFU per 100 mL	< 126 CFU per 100 mL	No detectable living organisms
Intestinal <i>Enterococci</i>	< 100 CFU per 100 mL	< 33 CFU per 100 mL	No detectable living organisms
Toxicogenic <i>Vibrio cholerae</i>	< 1 CFU per 100 mL <b>or</b> < 1 CFU per g wet weight of zoological sample	< 1 CFU per 100 mL <b>or</b> < 1 CFU per g wet weight of zoological sample	No detectable living organisms

As shown in Table 4, the ballast water treatment standards are based on the number of viable organisms in the treated ballast water. This approach differs from the normal convention used to describe the ability of a treatment technology to remove contaminants. Removal is generally classified as percent removal or log removal. In the case of ballast water treatment, the treatment system (single technology or series of technologies) would need to achieve at least 5-log (99.999%) bacteria removal and 7-log (99.99999%) virus removal to meet the CA Interim Standards. The required log removal for zooplankton is a little more difficult to estimate because the standard is no detectable living organisms. One method to estimate the needed log removal is to assume a zooplankton concentration of 100,000 zooplankton per m<sup>3</sup> of ballast water, an undetectable zooplankton count after treatment and sampling of 3 m<sup>3</sup> of ballast water, as required by IMO, and a minimum level of detection for zooplankton of 0.33 zooplankton per m<sup>3</sup>. Under these assumptions the required reduction is approximately 5-log. Using a similar methodology for protists (50 µm > microorganisms ≥ 10 µm), the minimum required reduction is also 5-log.

### 2.3 Current Ballast Water Treatment Approach

The majority of ballast water treatment literature and performance data is related to on-ship treatment technologies. Although there is limited information regarding onshore ballast water treatment, many of the on-ship treatment technologies have been adopted from traditional ground-based water treatment systems and could easily be adapted for on-shore ballast water treatment. The technologies used to treat ballast water are broadly grouped into three categories: physical separation, mechanical treatment, and chemical disinfection. Physical separation processes include coarse-screen filtration and hydrocyclone separation. Mechanical treatment technologies include ultraviolet light (UV), ultrasound, magnetic fields, and thermal treatment. Chemicals used in ballast water treatment include biocides, chlorine, ozone, hydrogen peroxide, and organic peroxides.

Given the numerous ballast water treatment technologies and potential combination of treatment technologies, the United States Environmental Protection Agency (EPA) (Lee II, 2010) screened 51 established and emerging ballast water treatment systems to determine which systems had credible performance data and met IMO discharge standards. A list of the five treatment combinations the EPA found to have credible data and meet USCG Phase 1 Standards is

provided in Table 5. Treated water effluent microorganism concentrations for each system are also provided in Table 5.

**Table 5 Removal of microorganisms by current on-ship technologies; table adopted from Balaji et al. (Balaji et al., 2014)**

Treatment train	Organisms $\geq$ 50 $\mu\text{m}$ (per $\text{m}^3$ )	Organisms 10 – 50 $\mu\text{m}$ (per mL)	<i>Escherichia coli</i> (cfu per 100 mL)	Intestinal <i>Enterococci</i> (cfu per 100 mL)	Toxicogenic <i>Vibrio cholerae</i> (cfu per 100 mL)
Filtration (40 $\mu\text{m}$ screen) + UV <sup>[1]</sup>	2.4 – 2.9	< 10	< 0.1	< 1	no data
Filtration (40 $\mu\text{m}$ screen) + ClO <sub>2</sub> <sup>[2]</sup>	0	0	0	0	0
Filtration + Electro chlorination <sup>[3]</sup>	0.2 – 9.0	0 – 6.8	0 – 1	< 1	< 1
Filtration + UV + TiO <sub>2</sub> <sup>[4]</sup>	< 4.4	< 2.3	< 1	< 1	< 1
Deoxygenation + Cavitation <sup>[5]</sup>	< 4.0	no data	< 10 – < 160	< 40 – < 45	no data

[1] Hyde Guardian treatment system manufactured by Hyde Marine

[2] Ecochlor treatment system manufactured by Ecochlor

[3] SiCURE treatment system manufactured by Siemens

[4] PureBallast treatment system manufactured by Alfa Laval

[5] NEI-Mitsubishi VOS treatment system manufactured by Mitsubishi

The ballast water treatment system combining deoxygenation and cavitation met all IMO D2 standards but exceeded all CA Interim Standards. The ballast water treatment systems using filtration before disinfection met CA Interim Standards for allowable *E. coli*, Intestinal *enterococci*, and *Vibrio cholerae* concentrations. One important note regarding reported *E. coli* Intestinal *enterococci*, and *Vibrio cholerae* removals is the natural marine water concentrations are often already lower than the treatment standard; thus, these microorganisms may not be the best indicators of full-scale ballast treatment system performance. The treatment system combining filtration and ClO<sub>2</sub> was the only technology that met all IMO 2D and CA Interim Standards. One reason the on-ship filtration systems do not remove more organisms greater than 50  $\mu\text{m}$  and organisms between 10 – 50  $\mu\text{m}$  is the relatively coarse filters used ahead of disinfection. Coarse filters are required for on-ship treatment because high volumes of ballast water must be filtered over a short period of time – flowrates range from 250  $\text{m}^3/\text{hr}$  (1,100 gpm) to 5,800  $\text{m}^3/\text{hr}$  (26,000 gpm) – in a small physical footprint (ABS, 2011).

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## Section 3 On-shore Treatment Technologies

Ballast water flowrates and other on-ship operational limitations and site constraints can be overcome using onshore treatment facilities. Flow equalization tanks can be used to regulate flow, a larger footprint can be used to accommodate larger treatment systems, and there are fewer limitations on process power requirements. Thus, tighter filters capable of removing particles ranging from 0.01  $\mu\text{m}$  – 2.0  $\mu\text{m}$  can be used for onshore ballast water treatment. The disinfection step can also be optimized using onshore treatment by designing optimized mixing systems and chemical contactors. The following sections outline the advantages, disadvantages, costs, and treatment efficacies of onshore filtration and disinfection technologies for ballast water treatment.

### 3.1 Physical Separation Processes

Dual-media and membrane filtration processes with coagulation as pretreatment step were evaluated for onshore ballast water treatment. In a full-scale installation, 80 to 120  $\mu\text{m}$  micro-screens may be needed to prevent barnacles, which have an approximate size of 130 to 150  $\mu\text{m}$  in their embryonic phase, from growing in downstream treatment processes.

#### 3.1.1 Coagulation, Flocculation, and Sedimentation

Coagulation is not a physical treatment process; however, it is used in conjunction with filtration to improve particle removal. Flocculation is implemented downstream of coagulation to allow the particles to agglomerate into larger particles and sedimentation is used to settle the particles out of suspension prior to filtration. Sedimentation is typically used when the average source water turbidity exceeds 30 NTU or spikes above 50 NTU over several hours (Voutchkov, 2013).

##### 3.1.1.1 Description

Coagulants are used in water treatment to neutralize negatively charged organic particles. The neutralized particles agglomerate during the flocculation step into large flocs, which are more easily settled and removed during filtration. Coagulation is most effective on waters containing higher turbidity ( $> 0.5$  NTU) and particles greater than 0.5  $\mu\text{m}$  (Voutchkov, 2013). Oemcke and van Leeuwen (2003) sampled ballast water from 13 cargo ships and reported an average ballast water turbidity of approximately 10 NTU, above the minimum turbidity needed for effective coagulation. The coagulants most often used for seawater treatment are iron salts (e.g., ferric chloride and ferric sulfate). Aluminum salts are not a good choice for seawater applications because it is difficult to maintain aluminum concentrations at low levels in dissolved form (Voutchkov, 2013).

Sedimentation can be accomplished in low-rate sedimentation basins or high-rate enhanced sedimentation technologies. In sedimentation basins, the velocity of the treated water is substantially reduced such that particles can fall out of suspension. In high-rate sedimentation technologies (such as, tube settlers and inclined plates), the settling area is increased in a smaller volume by including inclined surfaces within the sedimentation basin. High-rate settlers are often used in locations with physical site constraints or for source waters with varying or high ( $> 100$  NTU) turbidity.

##### 3.1.1.2 Advantages

The performance of granular media and membrane filtration is improved with upstream coagulation, flocculation, and sedimentation. Granular media filters can be expected to remove

particles larger than 50  $\mu\text{m}$  without upstream coagulation; whereas, particles as small as 0.2  $\mu\text{m}$  can be removed in a granular media filter operated with coagulants (Voutchkov, 2010). Membrane filtration fouling is reduced with the addition of coagulants due to the coagulant binding with organic foulants (e.g., natural organic matter (NOM) and oils) (Yang, 2009, Valavala, 2011).

### 3.1.1.3 Disadvantages

Ferric chloride is corrosive to most metals, especially aluminum, copper and carbon steel, and is also corrosive to nylon (WERF, 2005). Therefore, pumps, meters, and other system components must be made from non-metallic material or exotic metal alloys. Chemical storage tanks, metering pumps, mixing system (in-line static or mechanical flash mixer), and double-walled piping system for chemical conveyance are required and increase overall treatment system capital and operations and maintenance costs.

The effectiveness of the coagulation step is highly dependent on the feed water chemistry and coagulant dose (Schäfer, 2001). This could be potentially problematic for ballast water treatment because the ballast water chemistry is likely different for each vessel docking in port. Ballast water collected in a bay will have a different composition (salinity, TSS, TOC, etc.) than ballast water collected in the open ocean. The ballast water composition may need to be determined before it is treated to ensure the proper coagulant dose is applied.

### 3.1.1.4 Chemical dosing

The required coagulant dose varies with the feed water temperature, pH, and TSS concentration. Common ferric chloride doses reported in the literature for seawater desalination plants vary greatly but a rule of thumb is the coagulant dose is approximately two times the source water turbidity in NTU (Voutchkov, 2013). Oemcke and van Leeuwen (2003) reported the average measured ballast water turbidity from thirteen vessels was approximately 10 NTU with a minimum and maximum measured turbidity of 0.7 NTU to 52 NTU, respectively. Assuming the average measured turbidity is adequate for a preliminary design, the ferric chloride dose would be approximately 20 mg/L.

### 3.1.1.5 Chemical cost

Bulk chemical costs will vary depending on the location of the treatment facility. The bulk ferric chloride cost to a California Bay Area municipality, Central Marin Sanitation Agency (CMSA), was used for the purposes of this study to estimate the ferric chloride cost to a California shore-based ballast water treatment plant. CMSA paid \$484.7 per dry ton between July of 2015 and June of 2016 for bulk ferric chloride (40% solution).

### 3.1.1.6 Chemical storage and handling

Tanks used to store ferric chloride should be constructed of fiberglass reinforced plastic or rubber-lined steel. Pumps and piping should be non-metallic or rubber lined. Caution must be taken when handling ferric chloride because it is moderately toxic and corrosive. It is harmful to the eyes and skin, and respiratory track when inhaled.

### 3.1.1.7 Footprint

Coagulation has a much smaller footprint than the flocculation basins and settlers. The flocculation basin footprint will vary depending on the physical and chemical characteristics of the source water; however, typical contact times used to determine the size of the flocculation basin range from 10 – 40 minute and the basin depth is generally between 3.5 – 4.5 m (11.5 –

14.8 ft). The footprint of a high-rate plate settler, often used for seawater treatment and most likely needed to treat ballast waters with variable turbidity, can be calculated assuming a 10 – 20 minute contact time and a basin depth of 3.5 – 5 m (11.5 – 16.4 ft) (Voutchkov, 2013).

### 3.1.1.8 Capital cost

The cost of the coagulation and flocculation units is relatively low compared to the high-rate settlers. Voutchkov (Voutchkov, 2013) developed the following cost curve for high-rate plate settlers over a range treated water flowrates:

$$\text{High Rate Settler Cost} = 24(Q) + 75,000$$

where, filter cost is in dollars and Q is the high-rate settler design flow in m<sup>3</sup>/day. Ballast water treatment flows for each port studied and system sizing is provided in TM 4.

### 3.1.1.9 Residuals

Sludge produced from coagulation must be collected and properly disposed of per the Water Pollution Control Act Amendment of 1972. No estimates for the sludge production rate for seawater flocculation could be found in the literature. However, there are equations to estimate the sludge production rate as a function of the source water turbidity for drinking water treatment (Kawamura, 2000):

$$\text{Ferric Chloride Sludge Production} = [\text{Dose} \times 0.66 \times 8.34] + [\text{Turbidity} \times 1.3 \times 8.34]$$

where, ferric chloride sludge production is in pounds dry ferric chloride per million gallons water treated, dose is the ferric chloride dosage (mg/L), and turbidity (ntu) is the source water turbidity.

## 3.1.2 Filtration

### 3.1.2.1 Dual-media filtration

#### Description

Dual-media filters are commonly used in onshore freshwater and seawater treatment applications. These filters typically contain a coarse layer of anthracite (0.4 to 0.8 m in depth) over a fine layer of sand (0.4 to 2 m in depth). During filtration, water moves through the filter in the direction of coarse to fine media and the direction is reversed during a filter backwash. Larger particles are removed in the anthracite layer and smaller particles including silt and some microorganisms are removed in the sand layer. Backwash water can be treated by returning the backwash flow to the start of treatment system to be removed through sedimentation or can be directed to a sidestream treatment process. Backwash water and residuals management is discussed in further detail below.

Dual-media filters can be constructed as gravity or pressure filters. Gravity filters have a higher capital cost and larger footprint compared to pressure filters. However, gravity filters are often preferred over pressure filters because of lower operating (energy) costs, simpler inspection and maintenance, and better capabilities to handle changes in feed water composition. Another common configuration for seawater applications is a two-stage filter. In the first stage, a single coarse-media or dual-media filter is used and the second stage consists of a dual-media filter. Typically, 60 – 80% of the source water solids are removed in the first stage layer and 99% of the remaining solids, fine silt, and microalgae are removed in the second stage (Voutchkov, 2013). The effluent turbidity from a two-stage dual-media filter treating wastewater is normally less than 0.05 NTU.



## Advantages

Dual-media filters are capable of removing particles as small as 0.2 µm (with upstream coagulation) and provide treated water consistently low in turbidity for downstream disinfection processes. Dual-media filters exhibit lower clogging and have longer run times than single media filters due to large particles being captured by the anthracite reducing particle deposition in the fine sand layer. Additionally, media filter performance is more resilient to changes in source water pH and temperature compared to membrane filtration.

## Disadvantages

Dual-media filters provide limited removal of bacteria and viruses present in seawater. The concentration of contaminants in the filtered water can fluctuate with changes in source water turbidity, TSS, and pretreatment coagulant dose. This is an important consideration for ballast water treatment because the quality may vary between ships. Dual media-filters have a low removal rate of TOC (< 20%); although, TOC removal does increase with filter depth. Higher concentrations of TOC in the filter effluent can result in increased disinfection doses due to consumption of the disinfectant by the TOC.

## Filtration rate and footprint

Filtration rates for gravity and pressure driven dual media filters treating seawater range from 8 – 15 m<sup>3</sup>/m<sup>2</sup> h and 25 – 45 m<sup>3</sup>/m<sup>2</sup> h, respectively (Voutchkov, 2010). Filters used as a pretreatment in seawater desalination are normally backwashed every 24 – 48 hours and spent backwash volumes may be 2 – 6% of the source water flow depending on the source water quality (Voutchkov, 2013).

The footprint of a conventional dual-media filtration system is approximately 30 to 50 m<sup>2</sup> per 1,000 m<sup>3</sup>/day (1,200 to 2,100 ft<sup>2</sup>/mgd) of seawater treated (Voutchkov, 2013).

## Capital costs

Voutchkov (Voutchkov, 2013) developed cost curves for dual-media gravity filters used as a pretreatment in seawater desalination. The dual-media filter cost as a function of treatment capacity is defined by the following equation:

$$\text{Filter Cost} = 64(Q) + 380,000$$

where, filter cost is in dollars and Q is the dual-media filter design flow in m<sup>3</sup>/day.

## Energy demand

The energy demand of dual-media gravity filtration is typically less than 0.05 kWh per m<sup>3</sup> of water treated (0.2 kWh/1000 gal) in desalination pretreatment applications (Voutchkov, 2013).

## Residuals

The water recovery for media filtration ranges from 94 – 98% (Voutchkov, 2010). The amount of water lost through backwashing depends on the source water quality and filter/media type.

## Removal

Particles greater than 50 µm in size should be completely removed by dual-media filtration. Approximately 99% (2-log) of bacteria are removed through media filtration in drinking and wastewater applications. However, marine bacteria are smaller in size compared to freshwater bacteria, ranging in diameter from 0.3 µm – 50 µm (Garland Science, 2011). In one study, the reported removal of seawater bacteria in a dual-media filter with pre-coagulation was

approximately 80% (Matin, 2011). Guastalli et al. (2013), measured bacteria removals of approximately 60% through a dual-media filter treating seawater with upstream dissolved air floatation (DAF) treatment. The bacteria count in the filter effluent after combined DAF/dual-media filtration treatment was  $3 \times 10^5$  cells per mL.

### 3.1.2.2 Membrane filtration

#### Description

Membrane filtration processes such as microfiltration (MF) and ultrafiltration (UF) are commonly used to remove small particulate and colloidal matter (including microorganisms) from fresh water, wastewater, and seawater. MF and UF membranes have pores that separate solids from the source water through size exclusion. The nominal pore size of MF and UF membranes vary between manufacturers but are typically  $0.1 \mu\text{m}$  and  $0.02 \mu\text{m}$ , respectively. Similar to dual-media filters, MF and UF membranes must be periodically backwashed and cleaned to remove retained particles from the membrane surface and pores.

Membrane filtration systems can be separated into two categories: pressurized and submerged systems. Pressurized systems are operated under positive pressure and consist of membrane elements installed in pressure vessels or housings. The advantages of pressurized systems include the ability to operate at higher transmembrane pressures and to treat colder water sources with higher viscosity. Submerged systems are operated under slight vacuum pressure with membrane elements located inside of a tank. The advantages of submerged systems include a smaller physical footprint, lower energy usage, and ability to treat waters with highly variable turbidity.

#### Advantages

There are multiple advantages to membrane filtration for seawater treatment compared to conventional media filtration, these include:

- A smaller physical footprint. In certain circumstances the footprint of a membrane filtration system can be 50% smaller than a conventional media filter for seawater treatment (Voutchkov, 2013).
- More reliable filtered water (permeate) quality. Permeate quality is less susceptible to changes in source water turbidity, contaminant concentrations, and size and type of particulate matter (Lau et al., 2013).
- Lower coagulant dosing requirements. Coagulation requirements for membrane filtration can be 50 to 100% lower compared to conventional media filtration.

#### Disadvantages

Major disadvantages to membrane filtration are the pretreatment requirements, chemical cleaning regime, and membrane replacement costs. Fine or micro screens are needed as a pretreatment to membrane filtration to protect the membranes from physical damage; the necessity for fine/micro screens increases the capital cost of membrane filtration. The membranes must be cleaned to remove organic and inorganic foulants. Organic fouling is typically removed with sodium hydroxide or sodium hypochlorite and inorganic fouling is removed with citric, sulfuric, or hydrochloric acid. Membrane replacement intervals vary with source water quality and chemical cleaning frequency but a membrane life of 5 years is generally assumed.

### Filtration rate and footprint

Seawater desalination membrane filtration systems are designed to operate at a filtration rate (flux) between 40 to 80 L/m<sup>2</sup>-hr. The membrane permeability (flux per pressure applied) ranges from 75 to 500 L/m<sup>2</sup>-hr per bar depending on the membrane pore size.

The footprint of a UF system treating typical seawater water is 30 to 50% smaller compared to a granular media filtration unit designed for a loading rate of 8.5 to 12 m<sup>3</sup>/m<sup>2</sup>-hr. Assuming the UF system is 30% smaller under these conditions, the footprint of the UF system would be approximately 21 to 35 m<sup>2</sup> per 1,000 m<sup>3</sup>/day (840 to 1,470 ft<sup>2</sup>/mgd) of seawater treated (Voutchkov, 2013).

### Capital costs

Voutchkov (Voutchkov, 2013) developed lower and upper limit capital cost curves for membrane filtration used as a pretreatment in seawater desalination. The lower and upper membrane filtration treatment costs as a function of treatment capacity is defined by the following equations:

$$\text{Membrane Filtration Cost, Lower Limit} = 59(Q) + 830,000$$

$$\text{Membrane Filtration Cost, Upper Limit} = 105(Q) + 1,000,000$$

where, membrane filter cost is in dollars and Q is the dual-media filter design flow in m<sup>3</sup>/day.

### Energy demand

The energy demand of membrane filtration systems is up to six times higher compared to media filtration systems. The energy usage ranges between 0.2 – 0.4 kWh per m<sup>3</sup> of treated water (0.75 – 1.5 kWh/1000 gallons).

### Residuals

Membrane filtration systems require frequent backwashes and periodic membrane cleaning, which results in reduced water production. The overall water recovery for membrane filtration systems is typically between 88 and 94% (Voutchkov, 2010).

### Removal

MF and UF membranes would be expected to remove all particles greater than 10 µm. MF membranes would remove substantially less bacteria compared to UF membranes due to the MF membrane's larger nominal pore size. Guastalli et al. (Guastalli, 2013), measured bacteria removals of approximately 99.9% (3-logs) through UF membranes treating seawater with dissolved air floatation (DAF) pretreatment. The bacteria counts in the UF permeate after combined DAF/dual-media filtration treatment was 7 x 10<sup>2</sup> cells per mL.

## **3.1.3 Mechanical Treatment Summary**

Dual-media filtration and membrane filtration will remove virtually all particles greater than 50 µm in size. Although it is likely the majority of particles greater than 10 µm will be removed in dual-media filtration with coagulation, no data could be found on dual-media removal efficiency of 10 µm particles. Membrane filtration, MF and UF, will remove virtually all particles greater than 10 µm unless the membrane integrity is compromised. Bacteria and viruses will not be completely removed by dual-media or membrane filtration. However, the superior treatment provided by dual-media and membrane filtration will improve the efficacy of downstream

disinfection processes. A summary of the expected removal rates of dual-media filtration with pre-coagulation and membrane filtration for the regulated contaminants is provided in Table 6.

**Table 6 Comparison of microorganism removal by chemical treatment**

Treatment	Organism Class	Removal	Reference
Dual-Media Filtration	Organisms > 50 $\mu\text{m}$	$\approx 100\%$	Assumed
	$50 \geq$ Organisms > 10	$\approx 100\%$	Assumed
	Bacteria	0.4-log – 0.7-log	Martin, 2011; Guastalli, 2013
	Virus	Negligible	
	<i>Escherichia coli</i> <sup>[1]</sup>	0.4-log – 0.7-log	Martin, 2011; Guastalli, 2013
	Intestinal <i>Enterococci</i> <sup>[1]</sup>	0.4-log – 0.7-log	Martin, 2011; Guastalli, 2013
	Toxicogenic <i>Vibrio cholerae</i> <sup>[1]</sup>	0.4-log – 0.7-log	Martin, 2011; Guastalli, 2013
Ultrafiltration	Organisms > 50 $\mu\text{m}$	$\approx 100\%$	Assumed
	$50 \geq$ Organisms > 10	$\approx 100\%$	Assumed
	Bacteria	3-log	Guastalli, 2013
	Virus	Negligible	
	<i>Escherichia coli</i>	(5-log – 7-log)	Water Treatment, 2005; WHO, 2004
	Intestinal <i>Enterococci</i>	(2-log – 5-log)	Abbadi, 2012
	Toxicogenic <i>Vibrio cholerae</i>	3-log <sup>[1]</sup>	

[1] Assumed from reported removal of seawater bacteria

## 3.2 Physical Treatment

### 3.2.1 Ultraviolet

#### 3.2.1.1 Description

Ultraviolet (UV) radiation is commonly used for disinfection in water and wastewater treatment. The UV disinfection system consists of low- or medium-pressure mercury arc lamps, UV reactors, and ballasts. UV radiation works as a disinfectant by reacting with the microorganism's DNA and preventing the cell from reproducing. The optimum UV wavelength for disinfection is

between 250 and 270 nm. Low-pressure lamps emit light at a wavelength of approximately 254 nm. Medium-pressure lamps emit a broad spectrum of UV wavelengths (200 – 300 nm). Medium-pressure lamps have a greater germicidal strength and higher energy demand compared to low-pressure.

### 3.2.1.2 Advantages

UV is effective at inactivating most viruses, spores, and cysts. It is simple to install, has a short contact time (approximately 20 to 30 seconds), a small physical footprint, and does not require any chemicals; thereby, eliminating concerns with chemical storage, dosing, and handling. UV disinfection does not form any significant disinfection byproducts that are potentially harmful to humans or aquatic life (Liberti, 2003).

### 3.2.1.3 Disadvantages

One disadvantage to UV disinfection is pretreatment is often required to remove turbidity and TSS because particulate matter may shield microorganisms from UV light reducing disinfection performance (EPA, 2006). Another disadvantage to UV disinfection is it does not kill the cell but prevents the cell from reproducing. This can be problematic for a couple of reasons. First, microorganisms can repair DNA damaged during UV treatment in the absence of light (referred to as dark repair) and continue to reproduce. Second, the terminology describing the required state of the microorganism at discharge is unclear. The IMO and CA Interim Standards regulate the discharge by the number of “viable” or “living” organisms, and the guidelines for ballast water treatment technology approval define “viable organisms” as organisms and any life stages thereof that are living (Olsen, 2015). This language can be particularly problematic for obtaining approval for UV ballast water treatment systems; for example, the USCG recently concluded a reproduction/growth-based test is not appropriate for formal testing in the ballast water approval process.

### 3.2.1.4 Footprint

UV disinfection systems have a very small footprint compared to most other treatment disinfection technologies. For example, the dimensions of a Wedeco (Xylem Inc., NY) reactor designed to treat 5,400 m<sup>3</sup>/day (1.4 mgd) is 2 m x 0.4 m and a reactor designed to treat 43,000 m<sup>3</sup>/day (11.4 mgd) is 2.4 m x 0.7 m. The full UV disinfection system contains reactors, flow meters, and piping which requires more space than the individual reactors. In a report produced by the American Water Works Research Foundation (AwwaRF, 2005), equations were developed relating UV footprint to flow for systems with capacities greater and less than 17 mgd:

$$UV \text{ footprint, } Q < 17 \text{ mgd} = 84(Q) + 350$$

$$UV \text{ footprint, } Q > 17 \text{ mgd} = 40(Q) + 1220$$

Where, Q is the flow treated through the UV reactor in mgd. Additionally, the UV footprint curves were developed for a UV dose of 40 mJ/cm<sup>2</sup> and design UVT of 89% at 254 nm.

### 3.2.1.5 Capital cost

The New York State Energy Research and Development Authority (NYSERDA) estimated the equipment cost for a low pressure-high intensity UV disinfection system based on a dose of 30 mJ/cm<sup>2</sup> and average tertiary treated wastewater flowrates ranging from 1,900 m<sup>3</sup>/day (0.5 mgd) to 190,000 m<sup>3</sup>/day (50 mgd). The minimum UV transmittance and maximum TSS used in

NYSERDA's evaluation were 60% and 20 mg/L, respectively. The results from NYSERD's equipment cost estimates are provided in Table 7.

**Table 7 Estimated equipment costs for a low pressure-high intensity UV disinfection system (NYSERDA, 2004)**

WWTP Average Flow, m <sup>3</sup> /day (mgd)	WWTP Peak Flow, m <sup>3</sup> /day (mgd)	Equipment Costs, \$
1,900 (0.5)	4,700 (1.25)	60,000
9,500 (2.5)	24,000 (6.25)	220,000
28,000 (7.5)	72,000 (19)	500,000
76,000 (20)	190,000 (50)	1,090,000
190,000 (50)	470,000 (125)	2,500,000

### 3.2.1.6 Energy demand

The estimated energy demand of low pressure-high intensity and medium pressure UV systems is 0.2 kWh/m<sup>3</sup> (0.05 kWh/1000 gallons) and 0.6 kWh/m<sup>3</sup> (0.15 kWh/1000 gallons), respectively (AwwaRF, 2001).

### 3.2.1.7 Operations and maintenance

As part of NYSERDA's UV evaluation they estimated the annual operations and maintenance (O&M) costs of the low pressure-high intensity UV disinfection system over the same range of flowrates. The estimated annual cost normalized to cubic meter treated per day are presented in Table 8.

**Table 8 Estimated Annual O&M Costs for a low pressure-high intensity UV disinfection system (NYSERDA, 2004)**

WWTP Average Flow, m <sup>3</sup> /day (mgd)	WWTP Peak Flow, m <sup>3</sup> /day (mgd)	Annual O&M Costs, \$/m <sup>3</sup>
1,900 (0.5)	4,700 (1.25)	0.006
9,500 (2.5)	24,000 (6.25)	0.004
28,000 (7.5)	72,000 (19)	0.004
76,000 (20)	190,000 (50)	0.004
190,000 (50)	470,000 (125)	0.004

### 3.2.1.8 UV dose and removal

The UV dose is defined as the product of the average UV intensity multiplied by the contact time of the source water in the reactor. The required UV dose varies depending on the quality of the water and aquatic organism. UV disinfection is more effective on smaller organisms such as bacteria and viruses than larger marine organisms. Oemcke et al. (2004) were able to achieve 2-log inactivation of marine bacteria at a UV dose of 60 mJ/cm<sup>2</sup>. Sassi and Rytönen (2005) reported 6-log and 3-log inactivation of *E. coli* and *V. cholerae*, respectively, at a relatively low UV dose of 20 mJ/cm<sup>2</sup>. The UV dose required to inactivate larger marine organisms has been to be up to 200 mJ/cm<sup>2</sup> (Oemcke et al., 2004, Kazumi., 2007).

**Table 9 Log inactivation of ballast water microorganisms by UV disinfection**

Organism Class	Removal	UV Dose, mJ/cm <sup>2</sup>	Reference
Organisms > 50 µm	Low		
50 ≥ Organisms > 10	Low		
Bacteria	2-log	60	Oemcke et al., 2004
Virus <sup>[1]</sup>	2-log, 4-log	100, 190	EPA Water Treatment Manual, 2011
<i>Escherichia coli</i>	6-log	20	Sassi and Rytönen, 2005
Intestinal <i>Enterococci</i> <sup>[1]</sup>	3-log	50	Hijnen et al., 2006
Toxicogenic <i>Vibrio cholerae</i>	3-log	20	Sassi and Rytönen, 2005

[1] Removal reported for freshwater

### 3.3 Chemical Treatment

#### 3.3.1 Ozone

##### 3.3.1.1 Description

Ozone is a strong oxidant that disinfects by destruction of cell walls, nucleic acids and other biological molecules. Ozone is generated by passing an electrical current through air or pure oxygen. Gaseous ozone is bubbled through the water in the ozone contactor. Off gases from the contact chamber must be destroyed before venting to the atmosphere. Dissolved ozone decomposes rapidly, therefore no chemical residual remains after disinfection and no quenching agent is needed in freshwater prior release of ozonated water into the environment. Seawater, however, contains high concentrations of bromide ion. Within seconds of contact time, ozone in seawater is converted into hypobromous acid (Cooper, 2002). Hypobromous acid is also an effective disinfectant, but is more stable than ozone. Quenching agents to remove residual hypobromous acid prior to discharge may be desired. Because in seawater oxidant residuals are not due solely to ozone, residual measurements are typically expressed as “total residual oxidant” (TRO) as equivalent mg L<sup>-1</sup> Cl<sub>2</sub> or Br<sub>2</sub>.

##### 3.3.1.2 Advantages

Due to the unstable nature of this oxidant it is generated on site and requires no shipping or storage. Due to the rapid decomposition of ozone, no additional chemical agents are needed to destroy residual ozone after disinfection; however, quenching agents may be needed to remove brominated oxidant residuals.

##### 3.3.1.3 Disadvantages

Ozonation is energy intensive. Ozone is corrosive and requires use of corrosion resistant materials. Ozone gas is an irritant and toxic and proper ventilation is required for worker safety. Byproducts formed during ozonation of seawater include hypobromous acid (meta-stable) and bromoform; bromate formation has been observed in some studies but not in others (Cooper, 2002).

##### 3.3.1.4 Chemical dosing

Several studies have reported ozone doses and contact times for on-ship ballast water treatment. On-ship ozonation systems tested in these studies often lacked fully optimized ozone contactors

to maximize ozone dispersal. On-shore treatment facilities with more efficient ozone contactors would likely require lower ozone doses and/or contact times than on-ship treatment facilities. In addition, some studies report applied ozone dosages (in mg/L O<sub>3</sub>) while others report measured TRO (in mg/L Cl<sub>2</sub> or Br<sub>2</sub>), complicating comparison of disinfection results.

After 10 hours at ozone loading rates of 0.7 to 1.3 mg/L-h Herwig (2006) measured a TRO of greater than 5 ppm, a 4-Log removal of bacteria, greater than 96% removal of zooplankton, 100% mortality of shrimp and minnows, but zero mortality of amphipods. Similarly, less than 5 h of ozonation time at total oxidant residuals of less than 1 mg L<sup>-1</sup> (as Br<sub>2</sub>) effectively eliminated marine invertebrate species (Perrins, 2006; Jones, 2006). Others have reported high doses of ozone are required to achieve 4-log removal of bacterial spores (5 to 11 mg L<sup>-1</sup> as O<sub>3</sub> for 6 h; Oemcke, 2005) and dinoflagellate phytoplankton (9 to 14 mg/L as O<sub>3</sub> for 24 h).

#### 3.3.1.5 Chemical storage and handling

No chemical storage is required, unless a quenching agent to remove oxidant residuals is desired.

#### 3.3.1.6 Chemical cost

No direct chemical costs, with the possible exception of a quenching agent, such as sodium bisulfite or similar.

#### 3.3.1.7 Energy demand

Ozone generation has a significant energy demand. Specific energy requirements are subject to the ozone generation system. A typical low-pressure air system requires a specific energy of 10 to 12 kWh/lb (22 to 26 kWh/kg) (Langlais, 1991).

#### 3.3.1.8 Capital cost

Capital costs for an ozonation facility include: ozonation equipment (i.e., ozone generators, feed gas preparation equipment and associated instrumentation for monitoring and controlling the plant), ozone destruction or recycling systems, power supplies, contactors and associated diffusion systems (Langlais, 1991).

#### 3.3.1.9 Operations and maintenance

At operating ozone facilities for water treatment, energy costs typically make up 65% to 80% of operations and maintenance (O&M) costs. Other costs, including operator time, parts replacement, preventative maintenance, make up the other 20% to 35% of the total cost (Langlais, 1991).

#### 3.3.1.10 Potential for disinfection byproducts

Byproducts formed during ozonation of seawater include hypobromous acid (meta-stable), and in the presence of free ammonia, hypobromous acid will react to form bromamines (meta-stable). A suite of disinfection byproducts may form upon reaction of brominated oxidants with dissolved organic carbon. These include, but are not limited to: trihalomethanes, haloacetic acids, halophenols, halopropanes, halobenzenes (Delacroix, 2013). Bromate is a well-known disinfection byproduct formed during ozonation of bromide-containing drinking water; however, bromate formation has been observed in some ballast water studies but not in others and may be dependent on site-specific variables such as organic carbon and pH (Cooper, 2002).



### 3.3.2 Chlorine – Sodium hypochlorite

#### 3.3.2.1 Description

Chlorine is one of the most commonly used disinfectants for water in the world. A common method of chlorine addition to water is sodium hypochlorite solution (typically as a 12.5% (125,000 ppm) solution). Disinfection efficacy is dependent on pH; hypochlorous acid (the dominant form below pH 7.4) is more effective than hypochlorite (the dominant form above pH 7.4). In seawater, hypochlorous acid reacts with high levels of bromide to form hypobromous acid, also an effective disinfectant. Oxidation residual measurements are therefore typically expressed as “total residual” (TRO) as equivalent  $\text{mg L}^{-1} \text{Cl}_2$  or  $\text{Br}_2$ .

#### 3.3.2.2 Advantages

Chlorination by sodium hypochlorite addition is simple and has low energy requirements.

#### 3.3.2.3 Disadvantages

Requires chemical storage space and secondary containment. Chlorine residuals are stable and addition of a quenching agent prior to discharge may be required. Substantial formation of toxic disinfection byproducts has been observed.

#### 3.3.2.4 Chemical dosing

Chlorine doses of 20 mg/L resulted in observable *E. coli* and anaerobic bacteria concentrations of 0 CFU/100 mL (Zhang, 2003) after 24 h of contact time. Two-log removal of the majority of phytoplankton spp. was observed at  $\leq 20$  mg/L chlorine; however, for one species tested, *platymonas* spp, doses up to 100 mg/L were required to achieve 2-log removal (Zhang, 2003). 100% amphipod mortality required a chlorine dose of 40 mg/L (Zhang, 2003). Similarly, Stocks et al. (2003) found that 2-log removal of marine biota including bacteria, algae and fish larvae could be achieved below 10 mg/L chlorine; while brine shrimp cysts required approximately 500 ppm chlorine.

#### 3.3.2.5 Chemical storage and handling

Carbon or stainless steels are not compatible with sodium hypochlorite unless lined with rubber, PVC or Teflon. Storage tanks made of fiberglass reinforced plastic or high-density polyethylene (HDPE) are commonly used for sodium hypochlorite. Sodium hypochlorite degrades slowly over time to form sodium chlorite, sodium chlorate and oxygen. The degradation rate is dependent on temperature, light, pH and the presence of metals, but typically occurs over days to weeks at ambient conditions (Black & Veatch, 2010).

#### 3.3.2.6 Chemical cost

The cost of sodium hypochlorite can vary based on geographic location and solution strength/quality. A recent (2015) AWWA manual of water supply practices reported a range of \$0.60 to \$1.00/gallon for 12.5% sodium hypochlorite (AWWA, 2015).

If a quenching agent is desired, addition chemical costs would apply.

#### 3.3.2.7 Capital cost

Capital costs for a chlorine disinfection facility include: sodium hypochlorite storage tank, sodium hypochlorite feed equipment, instrumentation for monitoring and controlling the plant. A storage and feed system for residual quenching may be desired.

The capitol cost of a sodium hypochlorite process equipment, excluding the cost of the contact basin, buildings, electrical work, site piping, etc. as well as contingencies and fees, can be estimated using the following relationship based on the plant flow rate and chlorine dose (AWWA, 2015):

$$y = 0.006x + 0.2654$$

Where:

$y$  = process equipment capitol cost (million \$ USD)

$x$  = lb/d equivalent chlorine dose =  $(Flow\ rate, mgd) (chlorine\ dose, mg/L) \times 8.34$

### 3.3.2.8 Operations and maintenance

12.5% sodium hypochlorite solution is corrosive, and a severe skin and eye irritant. Special training in the use of hazardous material is required for operations personnel.

Operations and maintenance costs for a chlorination facility include chemical costs, equipment maintenance costs and labor costs. Equipment maintenance costs can be estimated as 1% of process equipment costs while labor costs will vary depending on facility size and can range from 25-40% of equipment maintenance costs (AWWA, 2015).

### 3.3.2.9 Potential for disinfection byproducts

Byproducts formed during chlorination of seawater include hypobromous acid (meta-stable) and bromoform. In the presence of free ammonia, hypobromous acid will react to form meta-stable bromamines. A suite of disinfection byproducts may form upon reaction of hypochlorous acid and secondary oxidants with dissolved organic carbon. These include, but are not limited to: trihalomethanes, haloacetic acids, halophenols, halopropanes, halobenzenes (Delacroix, 2013).

## 3.3.3 Electrochlorination

### 3.3.3.1 Description

Electrochlorination disinfection is based on the electrolysis of seawater to generate hypochlorite. Some pretreatment of the seawater is required including screening or microstraining and in some cases, filtration. Seawater is passed through one or more electrolytic cells. In the electrolytic cell, chloride ions are oxidized to form chlorine gas which quickly reacts with water to form hypochlorous acid, and hydrogen ions are reduced to form hydrogen gas. The concentration of hypochlorous acid residual generated varies with the current and voltage applied across the electrolytic cell. The same mechanism of disinfection and pH discussed above for “Chlorine-sodium hypochlorite” also apply to electrochlorination. In seawater, hypochlorous acid reacts with high levels of bromide for form hypobromous acid. Oxidation residual measurements are therefore typically expressed as “total residual” (TRO) as equivalent  $mg\ L^{-1}\ Cl_2$  or  $Br_2$ .

### 3.3.3.2 Advantages

No chemical storage. Lower hypochlorite concentrations generated in situ do not require the same level of hazard management as the higher strength solutions used in chlorination by sodium hypochlorite.

### 3.3.3.3 Disadvantages

Flammable hydrogen gas is a byproduct, requiring blowers and proper ventilation. Minerals present in seawater can lead to scale buildup in the electrolytic cell and reduce electricity

transmission (Black & Veatch, 2010). Frequent cleaning of the electrolytic cells is required. Chlorine residuals are stable and addition of a quenching agent prior to discharge may be required. Substantial formation of toxic disinfection byproducts has been observed.

#### 3.3.3.4 Chemical dosing

Chlorine residuals of 3.5 ppm resulted in greater than 4-log removal of bacteria after 5 hours of contact time (Matousek, 2006). 15 ppm chlorine and a contact time for 12 hours resulted in 99% mortality of zooplankton (Dang, 2003). However, because the initial active agent is hypochlorous acid/hypochlorite, chemical dosing reported for sodium hypochlorite (above) are also applicable.

#### 3.3.3.5 Chemical storage and handling

No chemical storage is required, unless a quenching agent to remove oxidant residuals is desired.

#### 3.3.3.6 Chemical cost

No direct chemical costs, with the possible exception of a quenching agent, such as sodium bisulfite or similar.

#### 3.3.3.7 Energy demand

Energy requirements vary between manufacturers and applications. Seawater electrolyzer cells are more efficient than brine electrolyzer cells used in freshwater disinfection. A seawater hypochlorite generator requires 1.8 kWh/lb (4 kWh/kg) chlorine generated (Casson, 2003).

#### 3.3.3.8 Capital cost

Capital costs for an electrochlorination facility include: Water softener, softened water storage tank, soft-water heater/chiller, metering pumps, electrolytic cell, hydrogen dilution blowers, instrumentation for monitoring and controlling the plant, sodium hypochlorite seawater solution storage tank, sodium hypochlorite feed equipment.

The capital cost of process equipment for on-site sodium hypochlorite generation<sup>1</sup>, excluding the cost of the contact basin, buildings, electrical work, site piping, etc as well as contingencies and fees, can be estimated using the following relationship based on the plant flow rate and chlorine dose (AWWA, 2015):

$$y = 0.0011x + 3.9776$$

Where:

$y$  = process equipment capital cost (million \$ USD)

$x$  = lb/d equivalent chlorine dose =  $(Flow\ rate, mgd) (chlorine\ dose, mg/L) \times 8.34$

#### 3.3.3.9 Operations and maintenance

Maintenance activities include system oversight, cell cleaning and electrode replacement. Operating costs for a seawater hypochlorite generation system, including electric power (at \$0.10

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<sup>1</sup> This cost curve was generated for potable water treatment with on-site generation of a 0.8% hypochlorite solution. Cost of an onsite hypochlorite generation system using for ballast water may vary somewhat from this estimate, given that more pretreatment may be needed, but storage requirements for the hypochlorite solution may be reduced or eliminated.

kWh), labor, consumer price index and chemical price index inflation, and electrode replacement, have been reported at \$0.249/lb chlorine (Casson, 2003).

### 3.3.3.10 Potential for disinfection byproducts

Byproducts formed during chlorination of seawater include hypobromous acid (meta-stable) and bromoform. In the presence of free ammonia, hypobromous acid will react to form meta-stable bromamines. A suite of disinfection byproducts may form upon reaction of hypochlorous acid and secondary oxidants with dissolved organic carbon. These include, but are not limited to: trihalomethanes, haloacetic acids, halophenols, halopropanes, halobenzenes (Delacroix, 2013).

### 3.3.4 Chemical Treatment Summary

Due to the high levels of bromide ion present in seawater, regardless of the initial oxidant, ozone or hypochlorous acid, within seconds of chemical addition, the dominant form of oxidant will be hypobromous acid. Therefore, the chemical treatment methods described have many similarities with regard to disinfection efficiencies and byproduct formation.

Table 10 compares the treatment efficiency of chemical treatment for organisms in ballast water.

Table 10 Comparison of microorganism removal by chemical treatment

Treatment	Organism	Treatment Conditions	Removal, % (log)	Reference
Ozone	Virus <sup>[1]</sup>	0.09 – 8.1 ppm TRO <sup>[2]</sup> , 0.25 – 4 min	≥ 90% (1-log)	Liltved (2006)
	Marine bacteria	>5 ppm TRO, 5 – 10 h	≥ 99.99% (4-log)	Herwig (2006); Perrins (2006)
	Bacterial spores	9 – 14 ppm O <sub>3</sub> , 24 h	99.99% (4-log)	Oemcke (2004)
	Protozoa	>5 ppm TRO, 10 h	96-99% (2-log)	Herwig (2006)
	Phytoplankton	>5 ppm TRO, 10 h	17 – 135%	Herwig (2006)
		9 – 14 ppm as O <sub>3</sub> , 24 h	99.99% (4-log)	Oemcke (2005)
	Zooplankton	0.8 – 7 ppm TRO, 5-48 h	90 (1-log) – 100%	Herwig (2006); Perrins (2006); Gregg (2009)
Chlorine—sodium hypochlorite	Marine bacteria	1 – 20 ppm TRO, 24 h	99 (2-log) – 100%	Stocks (2003); Zhang (2003)
	Phytoplankton	<1-100 ppm TRO	99% (2-log)	Stocks (2003); Zhang (2003)
	Zooplankton	1 – 40 ppm TRO, 24 h	100%	Stocks (2003); Zhang (2003)
Electrolytic chlorine	Marine bacteria	3 – 4 ppm TRO, 5 h	> 99.99% (4-log)	Dang (2003); Matousek (2006)
	Phytoplankton	15 ppm TRO, 12 h	72 – 99% (2-log)	Dang (2003); Matousek (2006)

	Zooplankton	4 – 15 ppm TRO, 12 – 24 h	95 – 99% (2-log)	Dang (2003); Matousek (2006)
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[1] TRO = Total residual oxidant (reported as mg/L Cl<sub>2</sub> or Br<sub>2</sub>)

[2] This study reported removal of several pathogenic fish viruses in seawater as determined in laboratory testing. Seawater used in the study was high-quality influent water to an aquaculture installation and was filter sterilized prior to testing

## Section 4 Further Considerations

### 4.1 California's Interim Ballast Water Discharge Performance Standards

The CA Interim Standards for discharged ballast water quality are summarized in Table 4. In general, the ballast water treatment system must remove 100% of organisms greater than 50 µm in minimum dimension (5-log removal to be below the detection limit), eliminate organisms between 10 µm and 50 µm in minimum diameter to concentrations ≤ 1 organism per 100 ml (equivalent to 5-log removal), and remove 5- and 7-log of bacteria and viruses, respectively to meet the California standards. There have been multiple technologies summarized above designed to remove these contaminants and may meet the California standards if used in series. The proposed treatment train(s) is coagulation/flocculation/sedimentation followed by media or membrane filtration and lastly UV or chemical disinfection. The reported removal of the regulated ballast water contaminants by each proposed treatment step and total removal by potential treatment trains are provided in Table 11.

As shown in Table 11, each of the proposed treatment trains can achieve the required removal of organisms greater than 10 µm. Only the treatment trains including membrane filtration can meet the bacteria removal requirement (≥ 5-log) and none of the proposed treatment trains can meet the virus removal requirements under the assumed treatment conditions. Although virus removal was too low for each treatment train, virus removal can be increased for UV and chemical disinfection by changing the operating conditions.

**Table 11 Removal of regulated ballast water contaminants by proposed treatment steps and treatment trains**

Physical Treatment		Mech./Chem. Treatment	Total System Removal
<b>Coag./Floc./Sed.</b> <b>Removal:</b> Org. > 50 µm = Low 50 ≥ Org. > 10 = Low Bacteria = Negligible Virus = Negligible	<b>Media Filtration</b> <b>Removal:</b> Org. > 50 µm = 5-log 50 ≥ Org. > 10 = 5-log Bacteria = 0.7-log Virus = Negligible	<b>UV Disinfection</b> <b>Removal:</b> Org. > 50 µm ≈ Low 50 ≥ Org. > 10 ≈ Low Bacteria = 2-log <sup>[1]</sup> Virus = 2-log, 4-log <sup>[2]</sup>	<b>Treatment Train: Coag./Media/UV</b> Org. > 50 µm = <b>5-log</b> 50 ≥ Org. > 10 = <b>5-log</b> Bacteria = > <b>2.7-log</b> <sup>[1]</sup> Virus = <b>2-log, 4-log</b> <sup>[2]</sup>
		<b>Chemical Disinfection</b> <b>Removal:</b> Org. > 50 µm ≈ Low 50 ≥ Org. > 10 ≈ Low Bacteria = > 4-log <sup>[3]</sup> Virus = 1-log <sup>[4]</sup>	<b>Treatment Train: Coag./Media/Chem.</b> Org. > 50 µm = <b>5-log</b> 50 ≥ Org. > 10 = <b>5-log</b> Bacteria = > <b>4.7-log</b> <sup>[3]</sup> Virus = <b>1-log</b> <sup>[4]</sup>
	<b>Membrane Filtration</b> <b>Removal:</b> Org. > 50 µm = 5-log 50 ≥ Org. > 10 = 5-log Bacteria = 3-log	<b>UV Disinfection</b> <b>Removal:</b> Org. > 50 µm ≈ Low 50 ≥ Org. > 10 ≈ Low Bacteria = 2-log <sup>[1]</sup>	<b>Treatment Train: Coag./Membrane/UV</b> Org. > 50 µm = <b>5-log</b> 50 ≥ Org. > 10 = <b>5-log</b> Bacteria = > <b>5-log</b> <sup>[1]</sup>

	Virus = Negligible	Virus = 2-log, 4-log <sup>[2]</sup>	Virus = <b>2-log, 4-log</b> <sup>[2]</sup>
		<b>Chemical Disinfection Removal:</b> Org. > 50 µm ≈ Low 50 ≥ Org. > 10 ≈ Low Bacteria = > 4-log <sup>[3]</sup> Virus = 1-log <sup>[4]</sup>	<b>Treatment Train: Coag./Membrane/Chem.</b> Org. > 50 µm = <b>5-log</b> 50 ≥ Org. > 10 = <b>5-log</b> Bacteria = > <b>7-log</b> <sup>[3]</sup> Virus = <b>1-log</b> <sup>[4]</sup>

[1] Removal achieved at a UV dose of 60 mJ/cm<sup>2</sup>

[2] 2-log and 4-log removal based on UV doses of 100 and 190 mJ/cm<sup>2</sup>

[3] Removal based on a TRO ≥ 5 mg/L and HRT ≥ 10 hours

[4] Removal based on a TRO = 8.1 mg/L and HRT = 4 minutes

The lower virus removals, 2- and 4-log, shown in **Table 11** for UV disinfection were reported for UV doses of 100 and 190 mJ/cm<sup>2</sup>. The UV log virus inactivation has a linear relationship with the UV dose (EPA, 2006), which is a function of the UV lamp irradiance intensity and contact time. The EPA (EPA, 2006) provides tables summarizing UV dose requirements to achieve specific log virus inactivation. These UV doses are related to fresh water but should be applicable to ballast water because UV disinfection is not particularly affected by salinity, pH, or other water quality parameters not related to organic matter or suspended solids. By extrapolating from the EPA UV dose requirement table, the estimated minimum required dose to achieve 7-log virus removal would be 310 mJ/cm<sup>2</sup>.

Similar to UV disinfection, virus removal for chemical disinfection can be improved by increasing the dose. A common way to calculate the chemical disinfection dose is to multiply the chemical concentration at the end of treatment by the treatment time – this is referred to as Ct. The Ct used by Liltved et al. (Liltved et al. 2006) used to achieve 1-log virus removal presented in **Table 10** was approximately 32 mg-min/L. This Ct is almost 100 times lower than the Ct used to achieve the 4-log bacteria removal (Ct = 3,000 mg-min/L) shown in **Table 10**. Increasing the Ct by two orders of magnitude will definitely increase the virus removal but testing of the ballast water would be required to determine if a Ct = 3,000 mg-min/L is sufficient or if a higher Ct is required. In summary, 7-log virus removal should be achievable using UV and chemical disinfection at higher doses than have previously been tested. The exact UV or chemical dose to attain 7-log virus removal would need to be determined through testing.

## 4.2 Disinfection Byproducts

The treatment of ballast water, primarily with biocides, produces new compounds called disinfection byproducts. In many cases such compounds are harmless, but in some cases the nature and amount of these compounds can be found to be harmful. For example, if bromines are present in ballast water that is treated with chlorine, various concentrations of chloroform and bromoform will be present in the treated effluent.

The developed treatment plants should be tested at bench and full scale to measure these levels of disinfection byproducts in order to assess whether the byproducts will have a significant effect

on the receiving waters. Such studies may find that lower doses of biocides are needed to keep the disinfection byproducts within acceptable ranges. Such a finding might rule out a particular treatment process, require a reduction in the treatment dose, or require a lower dose in combination with additional treatment measures.

### 4.3 Compliance Monitoring

Compliance monitoring should be more easily achieved with an on-shore treatment facility because regulators do not have to contend with monitoring ballast water discharges from numerous ships arriving at different times. Instead, regulators can monitor and regulate the ballast water from a single point source. Additionally, operators of onshore facilities are only responsible for the treatment system and ensuring the treated effluent quality meets all standards. This oversight may be lacking for on-ship treatment systems because shipboard operators and maintenance staff are likely responsible for other equipment on the vessel such as engines, pumps, and boilers.

The methods for determining and maintaining compliance with the CA Interim Standards should combine current monitoring and compliance techniques used in drinking water treatment and risk management systems approaches. The EPA has established requirements and provides guidance for monitoring filtration, UV disinfection, and chemical disinfection processes to protect the public from waterborne pathogens. Several drinking water treatment compliance monitoring requirements/guidelines developed by the EPA and others that should be considered for the ballast water treatment technologies discussed in this report include:

- **Media filtration:** The EPA Long Term 1 Enhanced Surface Water Treatment Rule (LT1ESWTR) requires the media filter effluent turbidity to be recorded at least every 4 hours and must maintain an effluent turbidity  $\leq 0.3$  NTU. The purpose of this requirement is to ensure the removal of microorganisms, primarily cryptosporidium and giardia, is above the minimum log removal requirement. It is likely media filtration may remove less than 0.7-log marine bacteria, but a similar turbidity monitoring program could be established to maintain a minimum 0.5-log bacteria removal through the filters.
- **Membrane filtration:** The EPA Long Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR) permits for membrane filtration to be used but removal credits are based on the results from product-specific challenge and direct integrity testing. These tests provide a base-line for bacteria removal and should be adapted as part of a ballast water treatment compliance and monitoring plan. LT2ESWTR allows for the membrane permeate to be continuously monitored using turbidity measurements or particle monitoring. However, if the measurement exceeds a predetermined control limit a direct integrity test, such as a pressure decay test, must be conducted. In the pressure decay test water is drained from one side of the membrane, pressurized air is applied at a pressure below the bubble point (defined as the minimum pressure required to overcome the surface tension of a liquid in a fully-wetted membrane pore), and the pressure decay is measured over a specified amount of time. The decrease in pressure over time is measured and can be directly related to the size of the defect in the membrane. This method is very effective in detecting defects. It has been shown the pressure decay test can detect a 0.6 mm puncture in the wall of one of over 22,000 fibers in a membrane module (Guo et al., 2010). Combining online turbidity meters and particle counters with regular direct integrity testing should provide a reliable and robust monitoring system to ensure the membrane system is complying with the treatment goals.
- **UV disinfection:** Compliance monitoring for UV disinfection is achieved in drinking water treatment through initial validation and online dose monitoring (EPA, 2006). The



EPA requires the UV reactor to be validated for microorganism removal using test microorganisms with UV dose-response characteristics similar to the microorganisms being treated in the source water. During validation, a relationship between the UV dose and online monitoring parameters (UV intensity, flow rate, and UV transmittance (UVT)) must be established to provide a baseline for online dose monitoring during continuous operation. Online monitoring is achieved using the UV intensity set point or calculated dose approach. In the UV intensity approach, UV sensors are used to measure the UV intensity to ensure the delivered dose meets the minimum UV dose established during validation testing to achieve a specified microorganism removal. In the calculated dose approach, online UVT and flow measurements are input variables in a dose-monitoring equation that can be derived during validation testing or developed by the manufacturer. There are advantages and disadvantages to both approaches; however, for ballast water treatment the calculated dose approach may be preferred because the UV dose can be more easily adjusted for changes in ballast water characteristics discharged from different vessels.

- **Chemical disinfection:** Compliance monitoring is achieved in chemical disinfection processes for drinking water treatment using the Ct concept. Ct is the residual disinfectant concentration (C) after treatment times the disinfection time (t). The required Ct to remove a microorganism or group of microorganisms can be preliminarily demonstrated through jar testing and verified during full-scale testing. The Ct necessary to achieve the target microorganism removal is monitored in full-scale applications using flow meters to calculate the HRT in the chlorine contactor (t) and online probes to measure the residual oxidant at the end of the basin (C). The EPA requires the HRT in the chlorine contactor be adjusted using a baffling factor (accounts for deviations from ideal plug flow in the reactor) determined through tracer studies. This ensures the HRT and Ct is not over estimated. This system provides a robust and simple method for compliance monitoring, which should be easily implementable for ballast water treatment.

A monitoring strategy will need to be developed that incorporates monitoring, logging, and reporting of the above listed parameters. It is important to note that these parameters are mechanical, such as UV intensity sensors, rather than biological. Biological monitoring presents significant challenges when applied to the CA Interim Standards given the extremely low organism counts. That noted, the developing biological monitoring techniques could be used to corroborate the engineering parameters.

The ‘no detectable’ limit for organisms at 50 microns or larger deserves special consideration. It is suggested that rules for determining compliance with this metric should be developed. For example, should 100 or 10,000 liters of treatment effluent be examined to determine compliance? For example, should it be assumed that as long as engineering parameters are maintained, such as pressure differential across a membrane filter, then compliance is assumed. It is suggested that engineering parameters should be considered as the primary compliance monitoring method, and a practical amount of water for examination such as 1,000 liters be used for periodic biological monitoring.

In addition to the above compliance monitoring techniques, risk management approaches such as critical control points (as suggested by the EPA Ballast Water Advisory Panel (SAB, 2011)) should be implemented to decrease the likelihood of discharging treated ballast water that is not in compliance with the relevant standards.

## 4.4 Residuals Management

Residuals are generated from sedimentation and from backwashing dual-media and membrane filters. These residuals have a high concentration of contaminants that need to be disposed of or treated to avoid introducing high concentrations of invasive to the receiving water body. The residuals produced during sedimentation typically have high solids content and can be dewatered using centrifuges, belt presses, or other dewatering devices and can be economically hauled off site for land disposal. For treatment trains implementing coagulation, flocculation, and sedimentation, filter backwash water can be sent to the head of the treatment system and the backwash solids can be removed and disposed of with the settled ballast water solids. This may be the most effective residuals management option because it guarantees invasive species are not returned to the receiving body.

If sedimentation is not included in the treatment train or as a sidestream residual treatment process, the next option is to disinfect the residual stream in a separate reactor. The residual stream will have much higher concentrations of microorganisms compared to the raw ballast water. Due to the elevated concentrations, high disinfectant doses will be required to achieve microorganism concentrations below the CA Interim Standards. There may also be a concern with increased amounts of disinfection by products produced as a consequence of the disinfection dose.

## 4.5 Ballast Water Treatment at a Municipal Treatment Plant – Stockton Mass Balance

### 4.5.1 Background

The primary ballast water disposal and treatment option being considered in this study for the Port of Stockton is to blend the ballast water with municipal wastewater and treat the blended stream at the City of Stockton's Regional Wastewater Control Facility (RWCF). RWCF treats an average daily wastewater flow of 31.7 mgd to tertiary-level quality using a combination of biological, physical, chemical, and natural treatment processes. The required effluent quality from RWCF is defined in the facilities National Pollution Discharge Elimination System (NPDES) permit. The NPDES permit sets limits for the allowable concentration of nutrients, organic chemicals, suspended solids, and total dissolved solids (TDS) in RWCF's effluent. Blending ballast water with RWCF's normal wastewater flow should have a minimal impact on most of the contaminants regulated in the NPDES permit with the exception of TDS.

The average annual effluent TDS concentration in RWCF's effluent is 670 mg/L and the NPDES effluent TDS limit is 830 mg/L (estimated from NPDES permit specified conductivity limit of 1,300  $\mu\text{mhos/cm}$ ). Ballast water TDS concentrations (approximately 30,000 mg/L) are considerably higher and may limit the amount of ballast water that can be blended for disposal. To determine if blending ballast water with the wastewater would result in an effluent TDS above the allowable concentration, a blending analysis was conducted.

### 4.5.2 Blending Analysis

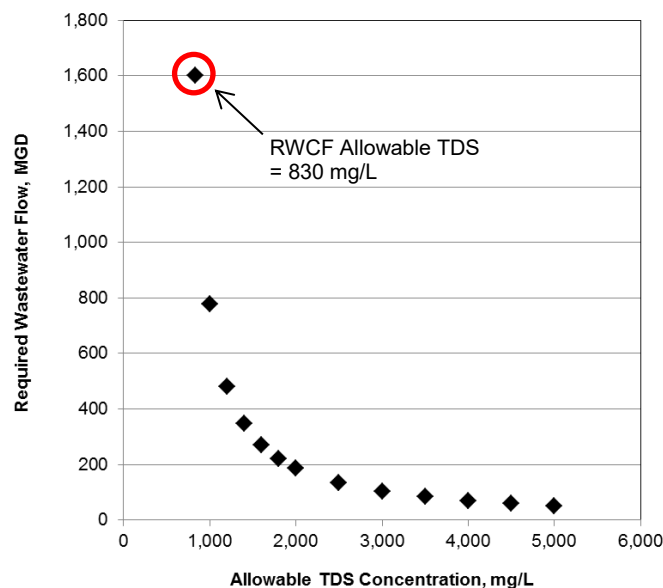
There were three blending analyses conducted to determine if ballast water blending was a viable disposal option. In the first blending analysis, the full ballast water flow was blended with the full RWCF influent flow to evaluate if the blended TDS was below 830 mg/L (NPDES TDS limit). The wastewater and ballast water flow and TDS used in the blending analysis and the results from the analysis are summarized in Table 12.

**Table 12 Results from the blending scenario assuming full ballast water and full RWCF influent flow were blended**

Water Type	Flow, m <sup>3</sup> /day (mgd)	TDS, mg/L
RWCF's Wastewater	120,000 (31.7)	670
Ballast Water	34,000 (9.0)	30,000
<b>Blended Water</b>	<b>154,000 (40.7)</b>	<b>7,100</b>

The TDS of the full RWCF wastewater and ballast water blend (7,100 mg/L) as shown in Table 1 far exceeds the allowable effluent concentration (830 mg/L). Considering this limitation, the second blending analysis was conducted to determine how much ballast water could be blended per day without exceeding the permit limit. The second blending analysis was done assuming the full wastewater flow, a wastewater TDS equal to 670 mg/L, and a ballast water concentration of 30,000 mg/L. The maximum amount of ballast water that can be blended per day under these assumptions without exceeding a blended concentration of 830 mg/L is 167,000 gallons – approximately 8.8 million gallons short of the total ballast water flow.

The third blending analysis was conducted to determine how much wastewater flow would be required to achieve a specified allowable blended TDS concentration. A range of blended TDS concentrations was evaluated because not all wastewater treatment plants will have the same TDS limits as RWCF. This blending analysis was done assuming a ballast water flow of 9.0 mgd, ballast water concentration of 30,000 mg/L, and a wastewater TDS concentration of 670 mg/L. The results from this analysis are illustrated in Figure 1.



**Figure 1 Required wastewater flow needed to meet a range of allowable blended TDS concentrations**

As shown in Figure 1, approximately 1,600 mgd of wastewater flow would be required to dilute the ballast water to RWCF's allowable concentration. A port the size of Stockton's would have to be located near a 500 mgd wastewater treatment plant to achieve a blended TDS concentration of approximately 1,000 mg/L. In summary, it is very unlikely blending with municipal wastewater will be a viable ballast water option unless the port is near a very large wastewater treatment facility, ballast water flows are very low, or the facility is permitted to discharge high TDS effluent.

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## Appendix A Study Overview and Definitions

This report is part of an overall coordinated study evaluating the feasibility of using shore-based mobile or permanent ballast water treatment facilities to meet California’s Interim Ballast Water Discharge Performance Standards.

## Study Overview

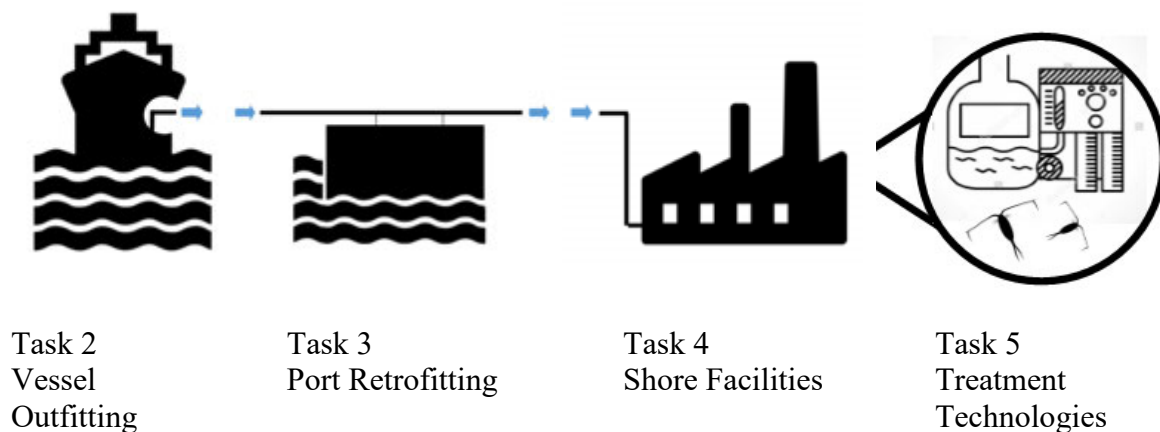
Marine vessels routinely uptake ambient sea or harbor water as ballast, transit to another port, and then discharge that ballast water. Unfortunately, the resulting ballast water discharges have been linked to the introduction of aquatic invasive species and harmful pathogens. In an effort to reduce or possibly eliminate further introductions, marine vessels are being required to manage ballast water discharges by a myriad of international, federal, and regional guidelines and rules. Vessels discharging in California will be required to meet an interim standard that is more stringent than international and U.S. federal standards.

In response, there has been significant development work and commercial installations of treatment systems located on board marine vessels themselves. However, there is a lack of data to determine if the treatment systems that are being installed on board marine vessels are capable of meeting the CA Interim Standards. Shore-based ballast water reception and treatment is under consideration as an approach to meet the CA Interim Standards.

This overall study evaluates the feasibility of such shore-based treatment systems in ten separate tasks, beginning with a review of shore-based treatment research and assessing potential all the way to cost estimates and an implementation timeline.

## Tasks Overview

Tasks 2 through 5 are submitted together to discuss the practical necessities for shore-based treatment system implementation, from the modifications onboard vessels through to the treatment technologies used in the facilities (see Figure 2).



**Figure 2** Scope of Tasks 2 through 5

Task 2 of the larger study assesses the retrofitting and outfitting of marine vessels, as part of the larger overall study on Shore-based Ballast Water Reception and Treatment in California. This report considers the feasibility and required modifications so that vessels can pump ballast water out of the ship to a new exterior piping manifold where shore facilities can receive and process the ballast water in accordance with California requirements.

Task 3 of the larger study discusses retrofitting of ports and wharves to receive ballast water from the vessels that need to transfer to on-site reception and treatment facilities, minimizing the disruption of normal port and vessel operations.

Task 4 of the larger study assesses the needed shore facilities to transfer, store and treat the ballast water once it leaves the marine vessel, determining the most cost-effective approach to meet performance standards and capacity requirements.

This Task 5 report assesses applicable types of treatment technologies available for shore-based reception facilities that show promise in the ability to meet the CA Interim Standards and how the efficacy of such systems can be measured.

## Case Studies Overview

The overall study uses location-specific case studies to cover the range of ports and terminals within California. A case study approach allowed the study team to develop a specific solution for each case, based on actual berth locations, estimated piping distances, specific water transfer rates and volumes, and applicable regulations, among other tangible aspects. After examining these cases, the estimated costs, timelines, and considerations discovered in the case study process will be scaled up to inform stakeholders and policymakers about statewide implementation.

Collectively, the five selected port districts constitute a rough cross-section of commercial shipping activity in California. The case studies were structured to ensure that a range of feasibility challenges are considered, including: vessel types; ballast water reception and conveyance; and ballast water storage and treatment approaches. For each case study, actual vessels and feasible methods of ballast water conveyance were combined with the three storage approaches and five treatment approaches that the study was required to assess. These approaches were assigned according to what approach promised to be feasible for each case study port. Table 13 summarizes the case studies and assigned approaches.

**Table 13 Summary of case studies**

Case Study	Port/Terminal	Vessel Type	Conveyance Approach	Storage Approach	Treatment Approach
1	Port of Stockton/East Complex	Bulk Carriers	Rail & Pipeline	New onsite tank	Existing WWTP <sup>[1]</sup>
2	Port of Oakland/TraPac Terminal	Containerships	New pipeline	New onsite tank	New onsite WWTP
3	Port of Hueneme/South Terminal Wharf 1	Automobile Carriers	Onsite storage	New onsite tank	Mobile shore-based treatment
4	El Segundo Marine Terminal	Tank Ships; ATBs	Offload to mobile marine vessel	Mobile marine vessel	Mobile, marine vessel-based treatment
5	Port of Long Beach/Cruise Terminal, Los Angeles/SA Recycling	Bulk Carriers & Passenger Cruise Ships	Offload to mobile marine vessel	New offsite tank	New offsite WWTP

## Definitions

ABS	American Bureau of Shipping
ANSI	American National Standards Institute
ASTM	An international standards organization.
ATB	Articulated Tug Barge
AWL	Height Above Waterline
AWWA	American Water Works Association
Ballast Water	Water taken on by a ship to maintain stability in transit.
Ballast Water Exchange	The process of exchanging a vessel's coastal ballast water with mid-ocean water to reduce concentration of non-native species in accordance with regulatory guidelines.
Ballast Water Management	The entire process of treatment and handling of a ship's ballast water to meet regulatory requirements and prevent spread of non-native species.
BMPF	Ballast Manifold Presentation Flange
Booster Pump	Pump, typically centrifugal, that adds additional pumping force to a line that is already being pumped.
BWDS	Ballast Water Discharge Standards
BWE	Ballast Water Exchange
BWM	Ballast Water Management
BWMS	Ballast Water Management System
BWTP	Ballast Water Treatment Plant
BWTB, BWT Barge	Ballast Water Treatment Barge
BWTS	Ballast Water Treatment System
Capture	Capture is the method by which ballast water is transferred onto or off a marine vessel.
CD	Chart Datum
CFU	Colony Forming Units
CMSA	California Marine Sanitation Agency
DAF	Dissolved Air Flootation
DIN	Deutches Institut für Normung (German Institute for Standardization)
Discharge	Discharge of ballast water is the method by which post-treatment ballast water is disposed of in compliance with applicable standards and regulations.
DOC	Dissolved Organic Carbon
DWT	Deadweight Tonnage
EPA	Environmental Protection Agency (US, unless otherwise noted)
Filtrate	Water that has been separated from any particulate matter (used to clean ballast water treatment filters).

GA	General Arrangement
GM	Metacentric height (a measure of a ship's stability).
gpm	Gallons per minute. Any measurements quoted in gallons of ballast water per minute will also be shown in MT of ballast water per hour, or MT/h.
HDPE	High-density Polyethylene
IMO	International Maritime Organization
ISO	International Organization for Standardization
JIS	Japanese Industrial Standards (organization)
L	Liter
Lift Station	Means of receiving a liquid, typically from a drain or low-pressure piping, and 'lifting' it with pump(s) to a different location such as a remote tank.
Lightering	Cargo transfer between vessels, commonly practiced to reduce a vessel's draft before entering port.
LT2ESWTR	Long Term 2 Enhanced Surface Water Treatment Rule
MARPOL	International Convention for the Prevention of Pollution from Ships
MF	Microfiltration
mg	Milligram
MG	Millions of gallons. Any measurements quoted in MG of ballast water will also be shown in MT of ballast water.
MGD	Millions of Gallons/Day
MHHW	Mean Higher High Water
MLLW	Mean Lower Low Water
MPA	Megapascal (unit of pressure)
MSL	Mean Sea Level
MT	Metric tons. One cubic meter of seawater is roughly equivalent to 1.025 MT, but this value varies depending on temperature and salinity of the water. In this report, conversions between volume and weight of seawater are merely approximate and assume 1 m <sup>3</sup> of seawater has a mass of roughly 1 MT, for convenience.
Navy Mole	A man-made peninsula in the Port of Long Beach that flanks entrance to the middle and inner harbor
NBIC	National Ballast Information Clearinghouse
NOM	Natural Organic Matter
Non-native Species	Species that are not indigenous to a particular region. Non-native species can be introduced to marine ecosystems through a ship's ballast water. "Invasive" species are non-native species with the potential to cause harm to the environment or human health.
NPDES	National Pollution Discharge Elimination System
NTU	Nephelometric Turbidity Unit
NYSERDA	New York State Energy Research and Development Authority



O&M	Operations and Maintenance (cost)
OCIMF	Oil Companies International Marine Forum
POTW	Publicly Owned [Wastewater] Treatment Works
PSU	Practical salinity units.
Residuals	Particulate matter collected from cleaning ballast water treatment filters.
ROM	Rough Order of Magnitude (cost)
Ro-ro	Roll-on/roll-off (vessels designed to carry wheeled cargo such as car, trucks, trailers, and equipment)
RWCF	Regional Wastewater Control Facility (e.g. City of Stockton, CA)
Shipboard Ballast Water Treatment	Ballast water management approaches that do not require support from shore-based infrastructure and are conducted entirely by a vessel's crew.
Shore-Based Ballast Water Management	Ballast water management approaches that require support from shore-based infrastructure in order to meet ballast water management requirements. Such infrastructure may include: means of transferring ballast water to a land-based or another marine vessel facility for storage and/or processing, deployment of shore-based equipment and personnel for onboard treatment approaches, etc.
Slurry	Mixture of filtrate and filter residuals resulting from cleaning ballast water treatment filters.
Slurry Handling	Slurry handling includes activities related to the storage, treatment, and discharge of filtrate and residuals collected from cleaning ballast water treatment filters.
SOLAS	International Convention for Safety of Life at Sea
Storage	Storage of ballast water includes provision of space and containment for ballast water, either pre-or post-treatment.
STS	Ship-to-Ship. Transfer from one marine vessel to another.
TDS	Total Dissolved Solids
TEU	Twenty-foot Equivalent Unit
TOC	Total Organic Carbon
Transfer	Ballast water transfer considers the logistics and equipment required to capture the ballast water from the marine vessel and transport to a reception and treatment facility.
Transport	Transport is the method by which ballast water is moved post-capture from marine vessels to remote, non-mobile reception and treatment facilities – either land-based or otherwise.
Treatment	Treatment includes the various methods to process ballast water such that it is suitable for discharge in compliance with applicable standards and regulations.
Treatment Approach	A general method for implementing ballast water treatment. Treatment approaches may include mobile systems, land-based facilities, shipboard systems, etc.

Treatment Technology	Specific techniques for removal or inactivation of organisms in ballast water (e.g., UV disinfection, filtration, ozonation, etc.)
TRO	Total Residual Oxidant
TSS	Total Suspended Solids
UF	Ultrafiltration
UKC	Underkeel Clearance
UL	A global independent safety consulting and certification company (formerly Underwriters Laboratories).
USCG	United States Coast Guard
UV	Ultraviolet Light
UVT	UV Transmittance
VLCC	Very Large Crude Carrier
WWTF	Waste Water Treatment Facility
WWTP	Waste Water Treatment Plant