Cruise Ship Wastewater Science Advisory Panel
Report to the Alaska Cruise Ship Initiative

Near-Field Dispersion of Wastewater Behind a Moving Large Cruise Ship
(Submitted June 26, 2001)

The Science Advisory Panel was asked to estimate the dilution of wastewater discharged from a moving cruise ship. In preparing the following report, a sub-group of the Science Advisory Panel (Atkinson, Beegle-Krause, George, Loehr) reviewed previous studies, and consulted marine architects and effluent discharge modelers. The full Science Advisory Panel endorses the conclusions contained within this report.

Executive Summary

The Scientific Advisory Panel (the Panel) recognizes that evaluation of cruise ship effluent dilution factors is a new area in environmental risk analysis. Cruise ships vary in hull design and discharge locations and the ambient oceanographic conditions are quite variable in coastal waters of Alaska (ambient currents, eddies, residence times and water column stability). Mathematical models exist for plume discharges and for ship wakes, but the two have not been combined to create a practical model for calculating ships effluent dispersion in the environment. The Panel found few studies directed specifically at ship effluent. Accordingly, the dilution achieved behind a moving self-propelled vessel has been estimated in a variety of ways. We looked at these various approaches, and then developed our own method, which we consider to be an estimate of the minimum dilution of wastewater discharged from a ship traveling at speeds from 6 to 18 knots. Our approach was to consider the ships' cross-section times the ship speed divided by the effluent discharge rate. We estimate that within less than 15 minutes[1] wastewater effluent is diluted by at least a factor 12,000 (1 part effluent to 12,000 parts seawater, or 1:12,000) for a large cruise ship traveling at 6 knots and discharging effluent at a rate of 200 m^3/hr. Greater dilutions will occur at higher speeds. Table 1 is a set of example calculations of dilution factors for different ships and speeds. Table 2 applies a dilution factor of 12,000 to the maximum and average concentrations of all constituents observed during the 2000 voluntary sampling and analysis program.

Far-field dispersion or dilution factors for a distance one mile (the nearest shoreline) from cruise ship track lines will be addressed in a subsequent report.

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[1] EPA's Technical Support Document for Water Quality-based Toxics Control (EPA /505/2-90-001) describes how an acute mixing zone should be established to prevent lethality to passing organisms. The guidance recognizes that the water quality criteria include duration of exposure considerations. Specifically, EPA allows that a drifting organism should not be exposed to 1-hour average concentrations exceeding the acute criteria, and that if travel time for a drifting organism through the acute mixing zone is less than 15 minutes, then a 1-hour average exposure would not be expected to exceed the acute criterion. The same demonstration is allowed for in Alaska's Water Quality Standards. This is the reason that the Panel has selected the time of 15 minutes following a cruise ship's passage as the basis for comparing to acute water quality standards. Comparison to more stringent chronic water quality standards at the 15 minute dilutions would be conservative and protective as well. The minimum mixing values that the Panel endorses are most likely attained in an even shorter time.

Review of previous studies

Kim (2000)[2] assumes cruise ship wastewater will be diluted into a standard mixing zone that is being considered under the ongoing development of Uniform National Discharge Standards (UNDS) for vessels of the Armed Forces. This zone is derived from the assumption of a mixing zone at any point in time as having a radius of 35 m and a depth of 20 m. The actual mixing zone for dilution purposes therefore becomes a "rectangular parallelopiped" or, more simply, a box with a cross section 70 m in width and 20 m in depth and an overall length dependent on the ship speed. Using this simple mass balance approach, Kim calculated a dilution factor of 78,000 for a typical cruise ship traveling at 6 knots and discharging wastewater at 200 m^3/hour. Though the Panel agrees with Kim that higher ship speeds should lead to greater dilution factors, the Panel is unsure that mixing down to 20 m should be assumed. The waters of Southeast Alaska often exhibit sharp density stratification at shallow depths that may restrict mixing to a shallower depth range than 20 m.

The Alaska SeaLife Center[3] (ASLC) provided a report that considered near-field dilution and far-field dispersion of graywater discharge from a typical cruise ship. In the ASLC-report a discharge model (CORMIX1) was used that considered the discharge to have a "plume". To calculate a near-field dilution the graywater discharge is treated as an effluent discharged from a pipe under the ship. The width of plume of the effluent is determined by modeling the effluent plume with the CORMIX1 model, and the depth of the plume is determined by a growing turbulent boundary layer along a flat surface (unlike the actual hull shape). The modeled plumes do not intersect the cross-section of the propellers (ASLC-report, Fig. 1, p.13) so mixing by propellers was not considered a significant component of the mixing process. The CORMIX1 model is an EPA approved model designed for discharges from a stationary outfall in a channel. Cruise ships are a nonstandard application of the model since the CORMIX model does not simulate the dynamics related to the ship's hull, displacement or propulsion system.[4]

The Panel believes this approach under-estimates the mixing process in the near-field, and is subject to the variations in the parameters used in the CORMIX1 model as well as the specific locations of the discharge pipes of each ship. Certain dilutions can be determined from this plume model. However, the plume that forms will undoubtedly be drawn into the propellers, and the dilution that occurs will be largely influenced by the propeller mixing and the returning displacement water from the ships' passage.

Several diffusion experiments were conducted in the 1970's at a deep-water dumpsite off the New York coast[5]. The discharge was from a towed barge where wake turbulence and re-combined displacement water caused effluent mixing. These observations found that wake dispersions produce initial dilutions up to a factor of 10,000 for a barge traveling at

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[2] Kim, D.K.; Cruise Ship Wastewater Dispersion Analysis (for International Council of Cruise Lines), August 25, 2000

[3] Colonell, J.M., Smith, S.V., Sipes, R.B.; Cruise Ship Wastewater Discharge into Alaskan Coastal Waters, Section 2 p.7-16, November 12, 2000

[4] Personal communication, Dr. Robert L. Doneker; Oregon Graduate Institute

[5] Csanady, G.T. 1980. An Analysis of Dumpsite Diffusion Experiments. pp. 109-129 B.H. Ketchum, D.R. Kester and P.K. Park (editors), Ocean Dumping of Industrial Wastes. Plenum Press, New York

6 knots. The lack of a propulsion system as in a cruise ship allowed the Panel to use these estimates as lower bounds for mixing estimates. The studies also suggest that mixing turbulence behind a vessel occurs in a vertical area (wake width and depth) 2.5 times the beam and 3 times the draft.

The panel also considered a sampling program from immediately behind a cruise ship, conducted near Ketchikan, Alaska[6]. Results of this limited study suggest that the dilution factor could be up to 583,000.

Discussion of the Science Advisory Panel's Approach

The Panel considered a simple approach to estimating dilution factors that is applicable to a variety of ships and locations of discharge ports. All propeller-driven ships have three mixing processes that contribute to diluting a discharge[7]:

1) *Turbulence from shear between the moving hull and the water*. As the ship moves through the water, the water immediately next to the hull is attached to the ship while water further away is undisturbed. The shear between the water dragged by the ship and the ambient water will cause some mixing as water progresses toward the aft section. The Panel assumes discharged waters will follow the hull of the ship to the aft section and that mixing within this boundary layer is not as significant as the subsequent processes.
2) *Turbulence from the motion of the propellers*. The counter-rotating propellers (one clockwise and one counterclockwise) that drive the ship extend to within 1 meter of the bottom of the hull (draft depth), and within a few meters of the surface. As the propellers operate they pull surrounding water through the propellers. The propellers also lower the local pressure and lift the water above them (similar to a jet engine generating "lift"). This water falls back down, causing turbulent mixing and bubble entrainment. Hence the Panel assumes that mixing occurs from the water's surface to the draft depth of the ship.
3) *Turbulence from the hull across the full width of the ship*. This is partly from the returning water displaced by the ship, and partly from the action of the propellers. The twin counter-rotating vortices produced by the propellers are less dense than the ambient water due to bubble entrainment. The vortices rise to the surface of the water within 1 to 2 ship lengths. Turbulence from the propellers is initially confined to the center half of the width of the ship, but soon spreads outward into a thinner layer about three times as broad as the vessel beam. Hence the Panel considers mixing the full width of the ship to be a minimum estimate.

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[6] ESL, LLC. 2000. Wastewater Dispersion Study: Distribution of Cruise Ship Effluent as Determined from Real-Time Collection of Water Column Samples; September 6-7, 2000

[7] The Panel thanks Dr. Guy Meadows, Society of Naval Architects and Marine Engineers, University of Michigan and Mr. Ed Glowacki of Glowaki Engineering for their time for discussions on ship design.

A simple estimate of the dilution of any substance discharged along the hull assumes a well-mixed effluent over a vertical plane with an area that equals the width of the ship times the draft of the ship. Thus we can calculate a dilution factor by comparing the rate the ship moves through a volume of water (cross section of ship times vessel speed) to the rate of the effluent discharge volume:

(ship width x ship draft x ship speed)/(volume discharge rate)

$(\_\_\_\_ m \quad x \quad \_\_\_\_ m \;\; x \; \_\_\_\_ m\ sec^{-1})/(\_\_\_\_\ m^3\ sec^{-1})$

For the typical ship described in the ASLC-Report and Kim (2000) the dilution factor is:

$$32\ m \times 8\ m \times \text{ship speed}\ (m\ s^{-1})\ /\ 0.06\ m^3\ s^{-1} \sim 4000 \times \text{ship speed}\ (m\ s^{-1})$$

Thus the dilution is proportional to ship speed and inversely proportional to the rate of effluent discharge. (0.06 $m^3\ s^{-1}$ or 200 $m^3\ hr^{-1}$ is the typical maximum discharge rate. Many ships at various times will discharge at a lesser rate.) A ship speed of 6 knots (3 m s^{-1}) gives a dilution factor of 12,000. Similarly, a ship speed of 12 knots (6 m s^{-1}) gives a dilution factor of 24,000. We estimate these dilution factors are minimum estimates (the dilution factor is not less than 10^4 or 10,000) for the physical processes involved.

Table 1 is a set of example calculations for different ships and speeds. Table 2 applies this dilution factor to the concentrations of all constituents observed during the 2000 voluntary sampling and analysis program and also presents Alaska's water quality standards for comparison.

The experiments at the deep-water dumpsite[5] suggest our mixing volume may be too small. In addition, the preliminary dilution study with fecal coliforms[6] indicates our model may underestimate the amount of mixing and dilution. The difference probably is in the transition between the near-field to far-field dilutions. We thus consider our dilution factors to be minimal estimates until further dilution studies indicate otherwise.

Because the model above is based largely on theoretical considerations, a dilution study with dye and other tracers should be performed to confirm the basic assumptions of the model, i.e. the vertical mixing area (width times draft) and the dependence of the dilution factor on ship speed.

Conclusions

1. The near-field dilution factors in the ASLC – report underestimate the amount of mixing and dilution.
2. The Science Advisory Panel recommends higher dilution factors that are proportional to ship speed, with no optimal ship speed for discharge.
3. A dilution experiment using an environmentally safe dye discharged from a cruise ship in field conditions could verify these dilution factor estimates and lead to more accurate estimates.

4. An appropriate model for ship effluent dispersion should be developed to allow others to leverage the knowledge gained from the Panel and any dye experiments. For example, the CORMIX model could be updated to handle moving ship discharges or existing wake turbulence models could be modified to add the ship discharge boundary conditions.

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Table 1
Dilution Factors for Cruise Ships Discharging Wastewater at an Average Rate of 200 m^3 per hour

	6 knots (3 m/s)	12 knots (6 m/s)	18 knots (9 m/s)
Ship One Length 215 m Beam 31 m Draft 7 m Displacement 45,000 m^3	10,500	21,000	31,500
Ship Two Length 252 m Beam 32 m Draft 8 m Displacement 65,000 m^3	12,800	25,600	38,400
Ship Three Length 297 m Beam 33 m Draft 8 m Displacement 78,000 m^3	13,200	26,400	39,600

Table 2
Estimated maximum and average concentrations attributable to detected priority pollutants in cruise ship waste water discharges after initial dilution, compared with Alaska's surface water quality standards for toxicants[8]
(Analysis of graywater and treated blackwater from 21 cruise ships, 2000)

MATERIAL	**Number of samples analyzed/ Number of samples material detected**	**DETECTION LIMIT µg/liter (approx. ppb)**	Maximum concentrations detected in graywater and/or treated blackwater discharge* (µg/liter or ppb)	Average Concentration (µg/liter or ppb)	Waste concentrations (µg/liter) after dilution, <15 minutes (dilution factor 12,000) Maximum/ Average	State Criteria for Marine Waters (µg/liter) ACUTE[9] or CHRONIC[10]
Volatiles by GC/MS						
Chloromethane	95/9	5.0	240	6.43	0.02/0.0005	None
Vinyl Chloride	95	2.0	Not detected			
Chloroethane	95	5.0	Not detected	Not detected		
1,1-Dichloroethene	95	2.0	Not detected	Not detected		
Methylene Chloride	95	5.0	Not detected	Not detected		
trans-1, 2-Dichloroethene	95	2.0	Not detected	Not detected		
1,1-Dichloroethane	95	2.0	Not detected	Not detected		
Chloroform	95/81	2.0	1500	48.3	0.125/0.004	None
1,1,1-Trichloroethane	95	2.0	Not detected	Not detected		
Carbon Tetrachloride	95/12	2.0	27	0.53	Negligible	50,000 (acute)
Benzene	95	2.0	Not detected	Not detected		

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[8] State-adopted aquatic life criteria will be shown unless there are no aquatic life criteria available. If not, federally promulgated criteria [National Toxics Rule(NTR)] may be shown that may include human health criteria. Chronic criteria are applied to ambient waters of the state. If acute criteria are shown, then there are no chronic criteria available.

[9] An acute criterion is the highest concentration of a pollutant to which aquatic life can be exposed for a short period of time (i.e., 1-hour, based on exposure to the average concentration) without deleterious effects.

[10] A chronic criterion is the highest concentration of a pollutant to which aquatic life can be exposed for an extended period of time (i.e., 4-day average) without deleterious effects. Human health criteria are also applied as chronic (70 year exposure to the chronic pollutant level, for the average lifetime of a human).

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1,2-Dichloroethane	95/10	2.0	1.9	0.09	Negligible	113,000 (acute)
Trichloroethene	95/5	2.0	71	0.87	0.006/0.00007	
Toluene	95/13	2.0	5.1	0.22	Negligible	5000 (chronic)
trans-1,3-Dichloropropene	95	2.0	Not detected	Not detected		
1,1,2-Trichloroethane	95	2.0	Not detected	Not detected		
Tetrachloroethene (or tetrachloroethylene)	95/13	2.0	740	13.2	0.06/0.001	450(chronic)
Dibromochloromethane	95/42	2.0	93	11.8	Negligible	6400(chronic)
Chlorobenzene	95	2.0	Not detected	Not detected		
Ethylbenzene	95/14	2.0	4.7	0.21	Negligible	430(acute)
Bromoform	95/41	2.0	170	12.2	0.015/0.001	No aquatic life criteria 3,600 (NTR human health criteria)
1,1,2,2-Tetrachloroethane	95	2.0	Not detected	Not detected		
Acrylonitrile	95	10	Not detected	Not detected		
2-Cholorethyl Vinyl Ether	95	10	Not detected	Not detected		

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Semivolatile Organics						
N-Nitrosodimethylamine	48	5.0	Not detected	Not detected		
Phenol	48/11	5.0	250	12.05	0.02/0.001	5800(acute)
bis(2-Chloroethyl) ether	48	5.0	Not detected	Not detected		
2-Chlorophenol	48	5.0	Not detected	Not detected		
1,3-Dichlorobenzene	48/1	5.0	380 (one detect)	7.9	Negligible	1970(acute)
1,4-Dichlorobenzene	48/7	5.0	350	7.7	0.03/0.0006	1970(acute)
1,2-Dichlorobenzene	48/1	5.0	390 (one detect)	8.12	Negligible	1970(acute)
Bis (2-Chloroisopropyl) ethe	48	5.0	Not detected	Not detected		
n-Nitroso-di-n-propylamine	48	5.0	Not detected	Not detected		
Hexachloroethane	48	5.0	Not detected	Not detected		
Nitrobenzene	48	5.0	Not detected	Not detected		
Isophorone	48	5.0	Not detected	Not detected		
2-Nitrophenol	48/1	5.0	5.4 (one detect)	0.11	Negligible	4850(acute)
2,4-Dimethylphenol	48	25	Not detected	Not detected		
bis(2-Chloroethoxy)methane	48	5.0	Not detected	Not detected		

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Semivolatile Organics						
Naphthalene	48/1	10	3.0 (one detect)	0.06	Negligible	2350(acute)
Hexachlorobutadiene	48	5.0	Not detected	Not detected		
4-Chloro-3-methylphenol	48	5.0	Not detected	Not detected		
Hexachloro-cyclopentadiene	48	10	Not detected	Not detected		
2, 4, 6-Trichlorophenol	48/2	5.0	3.2	0.08	Negligible	No aquatic life criteria 65 (NTR human health criteria)
2-Chloronaphthalene	48	5.0	Not detected	Not detected		
Dimethylphthalate	48/1	5.0	1.1 (one detect)	0.023	Negligible	3.4 (chronic)
Acenaphthylene	48	5.0	Not detected	Not detected		
Acenaphthene	48/1	5.0	7.7 (one detect)	0.16	Negligible	710(chronic)
2,4-Dinitrophenol	48	70	Not detected	Not detected		
4-Nitrophenol	48/1	5.0	8.0 (one detect)	0.17	Negligible	4850(acute)
2,6-Dinitrotoluene	48	5.0	Not detected	Not detected		

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Semivolatile Organics						
2,4-Dinitrotoluene	48	5.0	Not detected	Not detected		
Diethylphthalate	48/23	5.0	27.0	2.12	0.002/0.0001	3.4(chronic)
4-Chlorophenyl-phenylether	48	5.0	Not detected	Not detected		
1,2-Diphenyl hydrazine	48	5.0	Not detected	Not detected		
4-Bromophenyl-phenylether	48	5.0	Not detected	Not detected		
Hexachlorobenzene	48	5.0	Not detected	Not detected		
Pentachlorophenol	48	5.0	Not detected	Not detected		
Phenanthrene	48/2	5.0	3.1	0.13	Negligible	None
Anthracene	48	5.0	Not detected	Not detected		
Di-n-butylphthalate	48/11	5.0	20	1.57	0.25/0.0001	3.4(chronic)
Fluoranthene	48/1	5.0	1.2 (one detect)	0.03	Negligible	16(chronic)
Benzidine	48	90	Not detected	Not detected		
Pyrene	48	5.0	Not detected	Not detected		
Butylbenzylphthalate	48/6	5.0	9.6	0.34	Negligible	None
3,3'-Dichlorobenzidine	48	10	Not detected	Not detected		
Benzo(a)Anthracene	48	5.0	Not detected	Not detected		
Chrysene	48	5.0	Not detected	Not detected		
Benzo(b)fluoranthene	48	5.0	Not detected	Not detected		
Benzo(k)fluoranthene	48	5.0	Not detected	Not detected		
Dibenz(a,h)anthracene	48	5.0	Not detected	Not detected		
Benzo(g,h,i)perylene	48	5.0	Not detected	Not detected		

MATERIAL	**Number of samples analyzed/ Number of samples material detected**	**DETECTION LIMIT µg/liter (approx. ppb)**	Maximum concentrations detected in graywater and/or treated blackwater discharge* (µg/liter or ppb)	Average Concentration (µg/liter or ppb)	Waste concentrations (µg/liter) after dilution, <15 minutes (dilution factor 12,000) Maximum/ Average	State Criteria for Marine Waters (µg/liter) ACUTE[9]or CHRONIC[10]
Metals						
Antimony	48	variable	Not detected	Not detected		
Arsenic	48	variable	Not detected	Not detected		
Cadmium	48/3	variable	0.35	0.024	Negligible	9.3(chronic)
Chromium (total)	48/18	variable	53.0	7.32	0.005/0.0006	50()(VI) (chronic)
Copper	48/23	20	7100	789.6	0.59/0.066	2.9(acute)
Beryllium	48	1.0	Not detected	Not detected		
Nickel	48/15	40	630	33.8	0.05/0.003	8.3(chronic)
Zinc	48/23	5.0	1800	537.6	0.15/0.04	86 (chronic)
Lead	48/14	7.5	250	15.1	0.02/0.001	5.6(chronic)
Mercury	48/3	0.20	0.67	0.007	0.00005/ Negligible	0.025(chronic)
Selenium	48	3.0	Not detected	Not detected		
Silver	48/18	0.15	7.5	0.73	0.0006/0.00006	2.3(acute)
Thallium	48	15	Not detected	Not detected		
Cyanide, Total	48/5	10	73 (interferences?)	Interference?	0.02	1.0 (acute) (measure as free cyanide)