Report on the Analysis of Graywater Discharge

Presented to:
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FINAL
September 14, 2000

Combined Domestic Wastewater

1.0 EXECUTIVE SUMMARY

The cruise ship industry has experienced explosive growth in terms of size and popularity in recent years. Newer, bigger, and more capable ships are coming into service to meet the demands of the cruising population. Passengers are drawn to cruising by the adventure, relaxation, and entertainment afforded by the shipboard experience and by the serenity and beauty of the cruise locales. The natural splendor of destinations such as Alaska's Inside Passage and the Caribbean Islands is crucial to maintaining the attractiveness of these locales as places that people want to see and visit. In conjunction with the tremendous growth, and perhaps as an unavoidable by-product of it, the cruise industry and its ships have been under extreme scrutiny with respect to environmental performance and compliance. The Cruise Ship Wastewater Dispersion Analysis Report addresses one of the many facets of environmental performance and compliance, as they relate to cruise ship operations.

For this analysis, cruise ship graywater was characterized with respect to volume, flow rates, release frequencies, discharge durations, and locale. The concentrations of constituents to be expected at the discharge point are presented herein. Constituent concentrations were obtained from on-going sampling efforts that are an element of the Alaska Cruise Ship Initiative. Based on an assumption of the mixing and volumetric dilution effects in the path of a transiting ship, the diluted concentrations of cruise ship graywater constituents were calculated, as were the associated dilution factors. The analysis was based on a 3000-person (combined passenger and crew) cruise ship generating 4200 m^3 of graywater over a 7-day cruise period. The graywater discharge practices of such a ship, including the voluntary policy practices in effect for the Summer 2000 season, were considered. As the dilution calculations show, discharge constituents are diluted by a factor of 2.25×10^{-5} (44,400-times dilution) when a ship is moving at 4 knots. This dilution factor improves to 9.00×10^{-6} (111,000-times dilution) at 10 knots. As a result of dilution, the concentrations of graywater constituents fall by many orders of magnitude and are very low. As an example, copper, measured at 780 mg/L at the "end of pipe", dilutes to approximately 0.01 mg/L when the ship is transiting at 6 knots.

2.1 INTRODUCTION

Cruise ships operating in and around the waters of Alaska, and elsewhere, generate domestic wastewater in the course of accommodating their passengers and crew. Combined domestic wastewater, or "graywater" is comprised of galley, scullery, laundry, bath/shower, and sink drainage. It does not include sewage, or “blackwater”, which is exclusively human waste from toilets and urinals, plus medical facility sink drainage. Graywater is typically collected in tanks aboard cruise ships and held for recycling, transfer, or discharge. Graywater is currently not treated to any extent aboard ship. Cruise ships discharge graywater only as allowed by applicable regulations. U.S. Federal and international regulations allow discharge of graywater and properly treated blackwater virtually anywhere except in the Great Lakes, including in-port locations. However, cruise ship operators who are members of the International Council of Cruise Lines (ICCL) have voluntarily agreed to discharge graywater and treated blackwater only while ships are underway and not while in port.[1] An analysis of wastewater dispersion and the resulting dilution effects on the wastewater constituents was conducted to determine the concentrations of the various constituents that can be expected from the responsible discharge of cruise ship graywater and treated blackwater while a ship is underway.

2.2 SHIP CHARACTERISTICS

Cruise ship operations in Alaska were specifically chosen for this study because of the apparent ecological sensitivity of the Alexander Archipelago. The typical cruise ship operating in and around the waters of Alaska is 255 meters in length, with a 32-meter beam, and 8-meter light-load draft. This ship admeasures 74,000 gross tons and accommodates 2000 passengers per sailing. This “representative ship” undergoes several evolutions during a typical seven-day Alaska cruise, including embarking passengers in the originating port, providing meals, accommodations, and onboard entertainment, supporting passenger activities, transiting a course in excess of 700 nautical miles (n.m.), making port calls, and disembarking passengers at the destination port. The ship is of modern design and construction, with twin screws, and capable of making 23 knots. She is fitted with multiple bow and stern thrusters to aid maneuverability. The typical cruise ship can carry a crew of as many as 1000 personnel that serve in command, engineering, hotel services, food and beverage, and entertainment functions. The detailed characteristics of the typical cruise ship operating in Alaska waters are provided in Table 1.

TABLE 1
SHIP CHARACTERISTICS[1]

Characteristic	Value	Characteristic	Value
Length (meters, overall)	255	Disch Port Dist Below WL (meters)	5
Beam (meters, molded)	32	Disch Port Frame Location	Midship
Draft (meters, light-load)	8	Disch Port Angle, V-Plane (degrees)	-22
Displacement (gross tons)	74,000	Disch Port Angle, H-Plane (degrees)	0
Max Speed (knots)	23	Number of Collection Tanks	15
Cruise Speed (knots)	4 - 10	Total Tank Volume (m^3)	1180
Number of Shafts	2	Graywater Discharge Flow Rate (m^3/h)	200
Shaft Angle (degrees)	1.89	Graywater Discharge Temperature (degrees C)	30
Shaft Depth (meters)	5.1	Graywater Discharge Specific Gravity	1.0
Shaft Offset (meters)	6.3	Graywater Discharge Viscosity (N·sec/m^2)	7×10^{-4}
Shaft Rotation	Inboard	Graywater Discharge Salinity (% TDS)	1.5
Propeller Diameter (meters)	5.316	Graywater Discharge Conductivity	---
Number of Rudders	2	Graywater Discharge pH	6.1 – 6.4

Rudder Depth (meters)	6.585	Release Duration (hours)	2 - 6
Rudder Offset (meters)	6.94	Release Frequency (hours)	20 - 48
Number of Discharge Ports	2	Number of Passengers	2000
Discharge Port Diameter (mm)	140	Number of Crew	1000

[1] Ship characteristic data provided by member operators of the International Council of Cruise Lines.

WASTEWATER EFFLUENT DISCHARGE CHARACTERISTICS

3.1 System Description

Graywater is generated at galley, scullery, laundry, bath/shower, and sink locations throughout the ship and collected in up to 15 dedicated collection tanks with a combined capacity of approximately 1180 m^3. Once collected in the tanks, and as required by operational procedures and allowed by regulations, the graywater is pumped overboard. Motor-driven centrifugal pumps force the graywater overboard approximately 5 meters below the ship's waterline via multiple discharge ports. These discharge ports are located amidships and have a diameter of approximately 140 mm. Collection tanks are pumped by manual control when predetermined tank levels are reached. These levels range from 35% to 95% of maximum tank capacity. The level at which pumping is initiated is a function of many factors, including ship location, evolution, planned itinerary, and anticipated graywater generation rate. Typically, two engineering crew members work to ensure the safe and proper discharge of collected graywater.

3.2 Generation Rates

Graywater is generated at varying rates, as a function of passenger capacity, demographics, and activity. Estimates, as documented in the Alaska Cruise Ship Initiative Draft Report of the Work Groups, dated May 10, 2000, are that approximately 0.20 m^3 of graywater is generated per person per day. This generation rate equates to 4200 m^3 during a typical 7-day cruise, assuming a combined passenger/crew personnel count of 3000. This volume is collected as tank capacity allows. Given the available tankage on the typical Alaska cruise ship, graywater volume collected in tanks must be pumped periodically during the course of a seven-day cruise. Graywater can be collected for a maximum of 48 hours but controlled discharge every 20-48 hours is common.

3.3 Constituents and Concentrations

The key measurable constituents of graywater include organics, petroleum hydrocarbons, oils and greases, metals, suspended solids, oxygen demand, classical pollutants, nutrients, and coliform bacteria. Constituent concentration data for graywater has been estimated based on data made available by the ICCL. Further characterization efforts by cruise ship owners, operators, and regulatory agencies are underway, as an element of the Alaska Cruise Ship Initiative. Laboratory analyses are conducted in accordance with U.S. Environmental Protection Agency approved methods by certified laboratories. A listing of constituents typically found in graywater and their concentrations, as utilized for this analysis, is provided in Table 2.

TABLE 2
GRAYWATER CONSTITUENTS[1,2]

Constituent	Concentration (mg/L)	Constituent	Concentration (mg/L)
Chloroform	12.28	Ammonia	1,870

TPH	22,050	Oil & Grease	111,680
Barium	30	Phenols	90
Copper	780	pH	6.11
Nickel	20	Bis(2-Ethylhexyl) Phthalate	22.34
Zinc	80	Di-N-Octylphthalate	3.63
TSS	417,120	Fecal Coliform	2.4×10^7 col/100mL
BOD	814,620		

[1] Graywater laboratory analysis data provided by member operators of the International Council of Cruise Lines.

[2] Only those constituents found in concentrations above laboratory instrument detection limits are reported here.

3.4 Discharge Frequencies and Durations

Graywater generated by cruise ships can be diverted to discharge directly to the receiving waters, in accordance with applicable policy guidelines. Under this operating scenario, the graywater collection tanks are bypassed or serve only as sumps for the discharge pumps. Accordingly, there exist no operational limitations imposed by tank capacity. However, based on the typical operating mode, graywater must often be collected and discharged in a controlled fashion in order to comply with the distance-from-port and ship speed requirements of the voluntary discharge restriction policy. When the collection tanks and system of pumps, piping, and valves are used, the discharge frequency and duration can be controlled by the ship’s crew, to the extent allowed by tank capacity, total volume of graywater to be discharged, and total pump capacity. A typical Alaska cruise ship might discharge graywater for a period of two to six hours at total pump rates of 40 to 200 m^3/hour, according to data provided by member operators of the ICCL.

3.5 Mass Loadings

Assuming an average single graywater discharge evolution duration of four hours and a 200 m^3/hour discharge rate, 800 m^3 of collected graywater is pumped overboard during the evolution. For this scenario, the mass loading of constituents to the receiving waters can be calculated. A summary of mass loadings under the given scenario is provided in Table 3.

TABLE 3
CONSTITUENT MASS LOADING

Constituent	Concentration (mg/L)	Mass Loading (g)
Chloroform	12.28	9.824
TPH	22,050	17,640
Barium	30	24
Copper	780	624
Nickel	20	16
Zinc	80	64
TSS	417,120	333,696
BOD	814,620	651,696
Ammonia	1,870	1,496
Oil & Grease (non-regulated)	111,680	89,344
Phenols	90	72

pH	6.11	N/A
Bis(2-Ethylhexyl)Phthalate	22.34	17.872
Di-N-Octylphthalate	3.63	2.904
Fecal Coliform	$2.4 x 10^7$ col/100mL	$1.92 x 10^{14}$ col

3.6 Discharge Locality

The discharge of graywater can occur any time during a cruise, except as restricted by the voluntary graywater discharge policy. On a typical Alaska cruise, departing from and returning to Vancouver, British Columbia, and visiting ports of Juneau, Skagway, Hubbard Glacier, and Ketchican, the controlled discharge of collected graywater can occur at any point along the cruise route as long as the ship is sufficiently distant from port and underway making at least six knots. The restriction on graywater discharge when a ship is not cruising at this minimum speed is a provision of the voluntary policy. In locations other than Alaska, graywater and treated blackwater is not discharged until the ship is out to sea and beyond state waters.

4.0 DISPERSION ANALYSIS

The purpose of this analysis is to estimate the concentrations of wastewater constituents following their discharge from the ship.

4.1 Dilution Zone

The dilution zone is comprised of a volume of water in which homogeneous mixing occurs upon introduction of a substance, such as graywater. The dilution zone, much like an initial mixing zone, is defined as a column of water bounded on the surface by the locus of points a constant distance from the point of discharge. The depth of the dilution zone is defined as the depth of the waterbody to the "ocean floor" or 20 m, whichever is shallower. A dimension of 30 m was used in the analysis of cruise ship graywater dispersion because it approximates the initial mixing zone requirements of the State of Washington. The mixing inside the dilution zone is defined to occur over a four-hour period.

Dilution Zone Radius $= R_{dz} = 30m$

Dilution Zone Depth $= D_{dz} = 20m$

Dilution Zone Volume $= p \cdot (R_{dz})^2 \cdot D_{dz}$

$= p \cdot (30m)^2 \cdot 20m$

$= 56,547\ m^3$

4.2 Wake Dispersion

While the typical cruise ship is capable of steaming up to 23 knots, she often cruises at a reduced speed during much of the time when graywater maybe discharged. Driven by considerations of passenger safety, comfort, and enjoyment, the typical Alaska cruise ship is likely to cruise at speeds ranging from 10 to 20 knots. Using conservative ship transit speeds of 4, 6, and 10 knots, in conjunction with detailed ship characteristics, such as size, number, and location of propellers and rudder, relative locations of discharge ports and entrance angles, and discharge velocity, wake dispersion models can be developed and computer simulations can be conducted using available hydrodynamic modeling algorithms, such as CORMIX. While such modeling efforts were not within the scope of this analysis, it is clear that consideration of the wake dispersion effects will further reduce the resulting constituent concentrations of graywater. Incorporation of local tidal action and current considerations into the dispersion models will also result in increased discharge dispersion and decreased constituent concentrations. Additional dispersion as a result of these factors may be as much as 3 to 5 orders of magnitude.

4.3 Dilution Effects

Given that a typical cruise ship is transiting at speeds ranging from 4 to 10 knots (7.41 to 18.52 km/h) while discharging 200 m^3/hour of graywater over a four-hour period and that the applicable dilution zone is a cylinder of radius 30m and depth 20m, then overall dilution factors for the stationary and various transit scenarios can be calculated. These dilution factors are based strictly on the homogeneous mixing concepts associated with the dilution zone and do not take into consideration the additional dispersion effects afforded by ship wake, tidal, and current actions. The homogeneous dilution factors are calculated as follows:

Dilution Zone Volume = 56,547 m^3

Dilution Zone Radius = R_{dz} = 30m

Dilution Zone Depth = D_{dz} = 20m

Discharge Duration = t = 4h

Ship Transit Speeds = V_1 = 4 knots = 7,408m/h

= V_2 = 6 knots = 11,112m/h

= V_3 = 10 knots = 18,520m/h

Volume of Swept Zone = $2 \cdot (R_{dz}) \cdot (D_{dz}) \cdot (t) \cdot (V_{1,2,3})$

Volume @ 4 knots = $2 \cdot (30m) \cdot (20m) \cdot (4h) \cdot (7{,}408m/h)$

= 35,558,400 m^3

Volume @ 6 knots = $2 \cdot (30m) \cdot (20m) \cdot (4h) \cdot (11{,}112m/h)$

= 53,337,600 m^3

Volume @ 10 knots = $2 \cdot (30m) \cdot (20m) \cdot (4h) \cdot (18{,}520m/h)$

= 88,896,000 m^3

Discharge Volume = $(200\ m^3/h) \cdot (4h)$

= 800 m^3

Stationary Dilution Factor = $(800\ m^3) / (56{,}547\ m^3)$ (@ 0 knots) = 1.41475×10^{-2}

Transit Dilution Factor = $(800\ m^3) / (35{,}558{,}400\ m^3)$ (@ 4 knots) = 2.24982×10^{-5}

Transit Dilution Factor = $(800\ m^3) / (53{,}337{,}600\ m^3)$ (@

6 knots) = 1.49988×10^{-5}

Transit Dilution Factor= (800 m^3) / (88,896,000 m^3) (@ 10 knots) = 8.99928×10^{-6}

Ratio of Stationary to

Transit Dilution Factors = (1.41475×10^{-2}) / (2.24982×10^{-5}) (@ 4 knots) = 629

Ratio of Stationary to

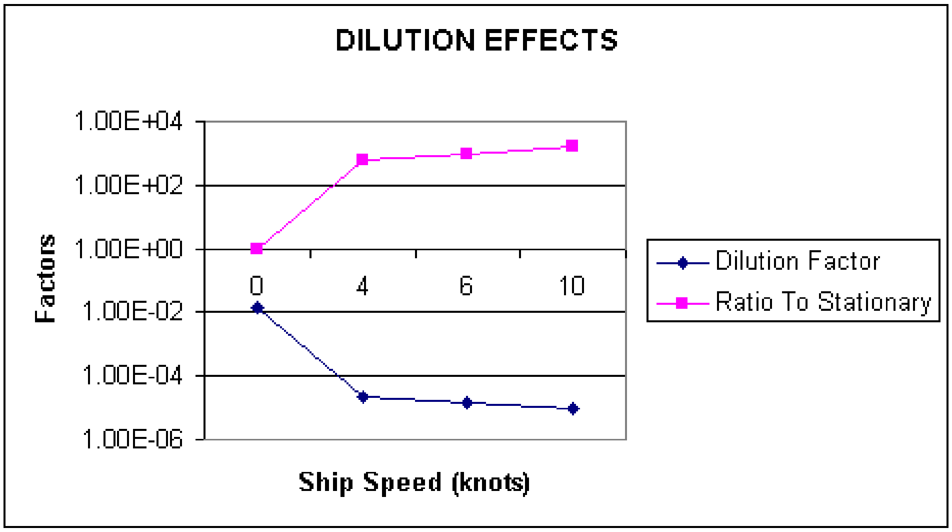
Transit Dilution Factors= (1.41475×10^{-2})/(1.49988×10^{-5}) (@ 6 knots) = 943

Ratio of Stationary to

Transit Dilution Factors = (1.41475×10^{-2})/(8.99928×10^{-6}) (@ 10 knots) = 1,572

As the calculations show, the discharge from a ship moving at 4 knots is approximately 630 times more diluted in the dilution zone than that from a stationary ship. The discharge from a ship moving at 6 knots is approximately 940 times more diluted in the dilution zone and the discharge from a ship moving at 10 knots is approximately 1570 times more diluted in the dilution zone. Plots of dilution factors and ratios as functions of ship speed are provided in Figure 1.

FIGURE 1



4.4 Results

Application of the homogeneous dilution factors to the constituent concentrations typical of cruise ship graywater discharge, results in diluted concentrations that might be expected within the proximity of the ship. A summary of the resulting constituent concentrations in the receiving waters, assuming homogeneous dilution, is provided in Table 4.

TABLE 4
DILUTED CONSTITUENT CONCENTRATIONS

Constituent	Initial Concentration (mg/L)	Stationary Dilution (mg/L)	4-knot Transit Dilution (mg/L)	6-knot Transit Dilution (mg/L)	10-knot Transit Dilution (mg/L)
Chloroform	12.28	0.1737	0.0002763	0.0001840	0.0001105
TPH	22,050	311.95	0.4961	0.3307	0.1984
Barium	30	0.4244	0.0006749	0.0004500	0.0002700
Copper	780	11.04	0.01755	0.01170	0.007019
Nickel	20	0.2830	0.0004500	0.0003000	0.0001800
Zinc	80	1.13	0.001800	0.001200	0.0007200
TSS	417,120	5901.21	9.38	6.25	3.75
BOD	814,620	11524.84	18.33	12.22	7.33
Ammonia	1,870	26.46	0.04207	0.02805	0.01683
Oil & Grease	111,680	1580.00	2.51	1.68	1.01
Phenols	90	1.27	0.002025	0.001350	0.0008100
pH	6.11				
Bis (2-Ethylhexyl) Phthalate	22.34	0.3161	0.0005026	0.0003350	0.0002010
Di-N-	3.63	0.05136	0.00008167	0.00005440	0.00003267

Octylphthalate					
Fecal Coliform	$2.4x10^7$ col/100mL	339,540 col/100mL	540 col/100mL	360 col/100mL	216 col/100mL

As the calculations show, the diluted constituent concentrations drop precipitously for a ship in transit as compared to a stationary one, and continue to drop progressively with increasing ship speed. For ship transit speeds of 4, 6, and 10 knots, the diluted concentrations are very low.

5.0 SUMMARY

Graywater discharged from the typical cruise ship is diluted by a very large volume of receiving water. Under stationary ship conditions, a dilution factor of $1.41475x10^{-2}$ is calculated. Under transit conditions at a ship speed of 4 knots, the dilution factor is $2.24982x10^{-5}$ (44,400-times dilution). At a ship speed of 6 knots, the dilution factor is: $1.49988x10^{-5}$ (66,700-times dilution) and at a ship speed of 10 knots, the dilution factor is $8.99928x10^{-6}$ (111,000-times dilution). These in-transit dilution factors represent approximately 630- to 1570-times greater dilution than under stationary ship conditions. Furthermore, the wake, tidal, and current actions that are normally present during discharge conditions provide many orders of magnitude more dispersion of the discharge constituents.

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[1] *Cruise ships operating in Alaska have voluntarily agreed to implement a policy of not discharging graywater or treated blackwater within the first ten (10) nautical miles that a ship travels after departing a port of call. Cruise ships have further voluntarily agreed to discharge only when underway at a speed of six (6) knots or greater. This voluntary policy, established as part of the Alaska Cruise Ship Initiative, is effective from May through September, 2000. Irrespective of this voluntary policy in Alaska, the dispersion analysis results are a function of factors such as discharge pumping rates, vessel speed, and mixing zone dimensions. The analysis results are not dependent on the location of the vessel.*