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Sampling Episode Report
Cruise Ship Plume Dilution Study
Skagway, Alaska

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ACKNOWLEDGMENT AND DISCLAIMER

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EXECUTIVE SUMMARY

Sampling Episode Report for Cruise Ship Plume Dilution Study

This Sampling Episode Report describes a plume dilution study conducted under the direction of the U.S. Environmental Protection Agency (EPA) in collaboration with the Alaska Department of Environmental Conservation (ADEC). This study, part of a survey conducted in Alaska by EPA's Ocean Survey Vessel *Bold* in July 2008, was designed to characterize near-field cruise ship discharge plumes from six cruise vessels while they were docked in Skagway Harbor, Alaska. Sampled vessels represented three cruise lines and a variety of advanced wastewater treatment system types, wastewater discharge flow rates, discharge port sizes, and port depths below the waterline. This study was conducted as a continuation of EPA's assessment of standards for sewage and graywater discharges from large cruise ships operating in Alaska.

Using *in situ* measurements of Rhodamine WT dye in the effluent plume, the survey team determined the location and concentration of each vessel's treated sewage and graywater discharge plume. A metering pump injected Rhodamine WT dye into the discharge line upstream of the discharge port, with a target dye discharge concentration of 700 μg/L (ppb). Dye concentrations in the resulting discharge plume were measured using a submersible fluorometer. Additional parameters (temperature, conductivity, depth, turbidity, and salinity) were measured simultaneously with plume discharge dye concentration, while manual notations of distance and location from the discharge port were made. Performing transects for plume characterization required approximately two hours per ship, with one ship tested per day. Measurements of the harbor current in the vicinity of the discharge plumes were collected using magnetic current meters. Dye concentrations in the discharge plume were found to decrease by a factor that ranged from approximately 40 to 90, depending upon ship, at a distance of 15 meters from the discharge port.

1. INTRODUCTION

This Sampling Episode Report describes sampling and analysis activities to characterize graywater and sewage discharge plumes from six cruise vessels (*Star Princess*, *Coral Princess*, *Ryndam*, *Celebrity Millennium*, *Norwegian Star*, and *Volendam*) discharging at port in Skagway Harbor, Alaska. This study, which was conducted from July 7 through July 17, 2008, is a collaboration between EPA's Oceans and Coastal Protection Division and the Alaska Department of Environmental Conservation (ADEC). This sampling study was partially funded via an interagency agreement between EPA and ADEC.

This study was part of a survey conducted in Alaska by EPA's Ocean Survey Vessel *Bold* and is a continuation of EPA's assessment of the need for additional standards for sewage and graywater discharges from large cruise ships operating in Alaska under the "Certain Alaskan Cruise Ship Operations" law (also known as "Title XIV"; 33 USC 1901 Note). The data and information gathered through this sampling episode were collected using EPA's authority under Section 308 of the Clean Water Act, as also provided by Title XIV. The cruise lines participating in the study voluntarily provided information and data gathered for and represented in this report, notwithstanding the above authority, in the interest of research for the improvement of wastewater treatment standards.

This plume dilution study was designed to provide information on near-field cruise ship treated sewage and graywater effluent discharge plume characteristics in harbor waters. The study will also provide preliminary information on whether these plumes behave as predicted by modeling performed by ADEC (Assessment of Cruise Ship and Ferry Wastewater Impacts in Alaska, 2004). ADEC used EPA's *Visual Plumes* model system[1] to simulate the dilution of discharges from both large and small vessels. ADEC's estimated dilution factor for initial dilution of discharges from stationary cruise ships in Skagway during a neap tide ranged from 5 to 60. The objectives of this study were to (1) determine the effluent dilution characteristics of discharges from stationary cruise ships; (2) track the near-field mixing dynamics of the effluent plume; and (3) provide information that can be used to validate the modeling studies (see Survey Plan, Appendix I).

Other sampling programs supporting EPA's assessment of cruise ship wastewater discharge standards in Alaska include two onboard sampling programs, conducted during the 2004 and 2005 Alaska cruise seasons, that focused on characterizing pollutants found in wastewater (graywater and sewage) onboard cruise vessels and evaluating the performance of the advanced wastewater treatment systems. The results of these sampling programs can be found on EPA's website at www.epa.gov/owow/oceans/cruise_ships/results.html.

Section 2 of this report describes the cruise vessels selected to participate in this study. Section 3 describes the data collection methodology. Section 4 presents a brief summary of the results. Section 5 provides a quality assurance assessment of the study.

[1] EPA's Visual Plumes model system is a Windows-based software application for simulating surface water jets and plumes. http://www.epa.gov/ceampubl/swater/vplume/

2. DESCRIPTION OF SELECTED CRUISE VESSELS

EPA selected the following six cruise vessels to participate in this plume dilution study:

- *Star Princess;*
- *Coral Princess;*
- *Ryndam*
- *Celebrity Millennium;*
- *Norwegian Star;* and
- *Volendam*.

The vessels participating in the survey represented three cruise lines and a variety of wastewater treatment system types, wastewater discharge flow rates, discharge port sizes, and port depths below the waterline. Each of the participating vessels operates an advanced wastewater treatment system to treat combined graywater and sewage. Table 2-1 presents the characteristics of the cruise vessels selected to participate in this study.

Table 2-1. Characteristics of Cruise Vessels That Participated in 2008 Plume Dilution Study, Skagway Alaska

Cruise Vessel (Parent Company)	Advanced Wastewater Treatment System Type	Discharge Flow Rate (m3/hour)	Discharge Port Outer Diameter (cm)	Discharge Port Depth Below Waterline (m)	Discharge Location
Star Princess (Carnival Corp.)	Hamworthy	25.5	20.3	2.5 (estimated)	Midship, Port
Coral Princess (Carnival Corp.)	Hamworthy	25	20.3	4	Midship, Starboard
Ryndam (Carnival Corp.)	Zenon	23	11.4	5 to 5.5	Midship, Port
Celebrity Millennium (Royal Caribbean Cruises, Ltd.)	Hydroxyl	22	27.3	5	Midship, Port
Norwegian Star (Norwegian Cruise Line)	Scanship	35	16.8	4.6	Midship, Starboard
Volendam (Carnival Corp.)	Zenon	36	11.4	6	Midship, Port

3. DATA COLLECTION METHODOLOGY

3.1 Pre-Sampling Activities

Visits to each of the six ships were conducted during the week prior to the start of the sampling episode. Visits were made to establish ship contacts, communications, and safety and emergency procedures, and to inspect sampling ports and associated fittings.

3.2 Sampling Schedule

Discharge plumes from six different cruise ships were monitored per the schedule in Table 3-1. Only one plume dilution study was conducted per day.

Table 3-1. Sampling Schedule

Cruise Vessel	Date of Study	Times of Study	Skagway Pier
Star Princess	July 10, 2008	1025 to 1230	Railway
Coral Princess	July 11, 2008	1040 to 1245	Railway
Ryndam	July 12, 2008	1025 to 1205	Railway
*Celebrity Millennium**	July 15, 2008	0950 to 1135	Railway
*Norwegian Star**	July 16, 2008	1000 to 1145	Ore
Volendam	July 17, 2008	1005 to 1140	Broadway

* Trial testing was also conducted on the *Celebrity Millennium* on July 7, 2008, and the *Norwegian Star* on July 9, 2008, to refine sample collection methodology.

3.3 Dye Injection Methodology

Metering pumps (Series 2001HEC-30 Variable Speed Peristaltic Pump, Flomotion Systems) were used to inject Rhodamine WT dye (Rhodamine WT Liquid, ORCO Organic Dyestuffs Corporation) into the cruise ships' treated sewage and graywater discharge. The pumps were installed downstream of the advanced wastewater treatment system, but as far upstream of the discharge port as possible so that multiple pipe bends and fittings provided thorough mixing of the dye.

Strap-on ultrasonic flow meters (BE 6000 Ultrasonic Flow Meter, Flomotion Systems) were installed on the discharge piping to record discharge rates (presented in Appendix G). Measured discharge rates were multiplied by the known Rhodamine WT dye feed stock concentration to calculate and adjust discharge dye concentration to attain the target concentration (discussed below). Discharge dye concentration also was measured directly on three cruise vessels (*Celebrity Millennium*, *Norwegian Star*, and *Volendam*) using a fluorescence sensor with a flow-through cell (SCUFA®, Turner Designs) installed on the discharge piping as close as possible to the discharge port. While the shipboard survey team was able to monitor discharge dye concentration via laptop computer connected to the SCUFA® sensor, it was not possible to electronically log these data. Therefore, the survey team kept manual logs of discharge dye concentrations. Tables F-1 through F-4 of Appendix F contain the raw data obtained from the fluorometer (see Section 5.1).

Trial dilution studies conducted on the *Celebrity Millennium* and the *Norwegian Star* revealed that the originally planned target discharge dye concentration of 100 ppb (see Survey Plan, Appendix I) was too low to be detected outside the cruise vessel (see Section 5.1, Accuracy and Calibration). Therefore, the target discharge Rhodamine WT dye concentration was increased to 700 ppb for most transects (Table 3-2). Target dye concentration was decreased during the *Star Princess* study because the plume was visible on the surface of the water (most likely because of the relatively shallow discharge port; see Table 2-1); this was the only vessel where the plume was visible on the surface of the water. Target dye concentration was increased during the *Coral Princess* study because the highly intermittent nature of the discharge and strong water currents made plume detection difficult (see Section 4.1).

Table 3-2. Target Discharge Rhodamine WT Dye Concentrations by Cruise Vessel

Cruise Vessel	Discharge Rhodamine WT Dye Concentration (ppb)
Star Princess	700 (cast 4), then 420 (casts 5 through 11)
Coral Princess	700 (casts 2 through start of 5), 875 (portion of cast 5), 1,050 (end of cast 5 through cast 7)
Ryndam	700
Celebrity Millennium	700
Norwegian Star	700
Volendam	700

Discharge dye concentrations are the product of the known initial dye concentration, dye injection rate, and discharge flow rate. While the initial dye injection concentration and dye injection rate were constant (with the exception of the *Coral Princess*; see Section 4.1), discharge flow rates varied, resulting in variability of the discharge dye concentration. Any analysis of the data collected in this study should consider this variability when calculating near-field discharge plume dilution.

On four cruise vessels, temperature, turbidity, and pH of the treated effluent also were recorded from the ship's wastewater treatment control panel. These data are provided in Appendix F. Similar data were not available for the remaining two ships.

3.4 Plume Monitoring Methodology

Dye was injected into the treated sewage and graywater discharge for approximately two hours on each cruise vessel. During that time, dye concentrations in the water outside the cruise vessel were measured to determine near-field plume dilution after discharge (the cruise vessels all were positioned so that the discharge ports faced the harbor and not the piers). Prior to dye injection, measurements were taken of background fluorescence concentrations in the water. These measurements verified that no background seawater fluorescence was detected above the detection limit of fluorometer, which was approximately 1.6 ppb. For most ships, a salinity depth profile also was performed to locate the halocline prior to dye injection.

Dye concentrations were measured using an *in situ* fluorometer (SCUFA®, Turner Designs) integrated into a Sea-Bird SBE-19 conductivity, temperature, and depth (CTD) sensor package (Sea-Bird SBE-19, Sea-Bird Electronics, Inc.) (Figure 3-1). This sampling array was

deployed from a rigid inflatable boat (RIB) that was conducting transects at low speed (Figure 3-2).

Figure 3-1. Sea-Bird SBE-19 CTD Sensor with Integrated SCUFA® Fluorometer

Figure 3-2. Rigid Inflatable Boat

One rope was used to control the depth of the towed array, while a second rope was used to control the distance of the towed array from the discharge port. This second rope was tied to

the bow of the RIB and attached to the cruise vessel via a hull magnet affixed just above the waterline at the location of discharge port. Sensor depth was recorded electronically by the sampling array, while RIB location relative to the hull magnet was recorded manually by the sampling team onboard the RIB. The RIB sampling team also monitored sensor measurements, including Rhodamine WT dye concentrations, in real time using a laptop computer. The following measurements were collected by CTD + SCUFA® sampling array at 0.5 second intervals during the plume transects: dye concentration (uncorrected; see Section 5.1); temperature; conductivity; depth (of the sensor array); turbidity; and salinity.

For most ships, a variety of transect types were conducted to provide detailed characterization of the discharge plumes (see Appendix A). Transects can be described by visualizing polar axes on the water surface, with the location of the hull magnet corresponding to the origin, and the array location and movement indicated by a radius (distance from cruise vessel) and polar angle (estimated in degrees by the RIB sampling crew) (see Figure 3-3). For example, 90° indicates the array is located to the right of the discharge port at the ship's hull, while 270° indicates the array is located to the left of the discharge port at the ship's hull. Four different types of transects were performed to characterize the discharge plumes:

- Arc. Array was moved in an arc (e.g., 90° to 270°) at a fixed distance from the hull magnet. Arc transects at varying water depths and distances from the hull magnet were the most common type of transect performed, and were the primary means to locate and characterize discharge plumes.

- Inward or Outward Profile. Array was moved toward or from a fixed position on the hull (i.e., the hull magnet) at a constant angle (e.g., 225°). Inward and/or outward profiles were performed after the location of the discharge plume was determined using arc transects. These profiles produced continuous dye dilution profiles determined by distance from the hull magnet.

- Stationary. Array was maintained at a fixed location (depth, distance, and angle from the ship) over a period of time. This profile produced a continuous dye dilution profile at a fixed array location as the plume moved past the array over time. This was the primary type of transect used for the *Star Princess* because the plume was visible on the surface of the water (most likely because of the relatively shallow discharge port on the vessel; see Table 2-1), therefore an arc transect was unnecessary to find the plume. This type of profile also was used frequently for the *Coral Princess*, where ship discharge flow rates were highly variable and/or intermittent.

- Depth Profile. Array was maintained at a fixed distance and angle from the ship while the array was raised or lowered through the water column. These profiles produced continuous dye dilution profiles by depth.

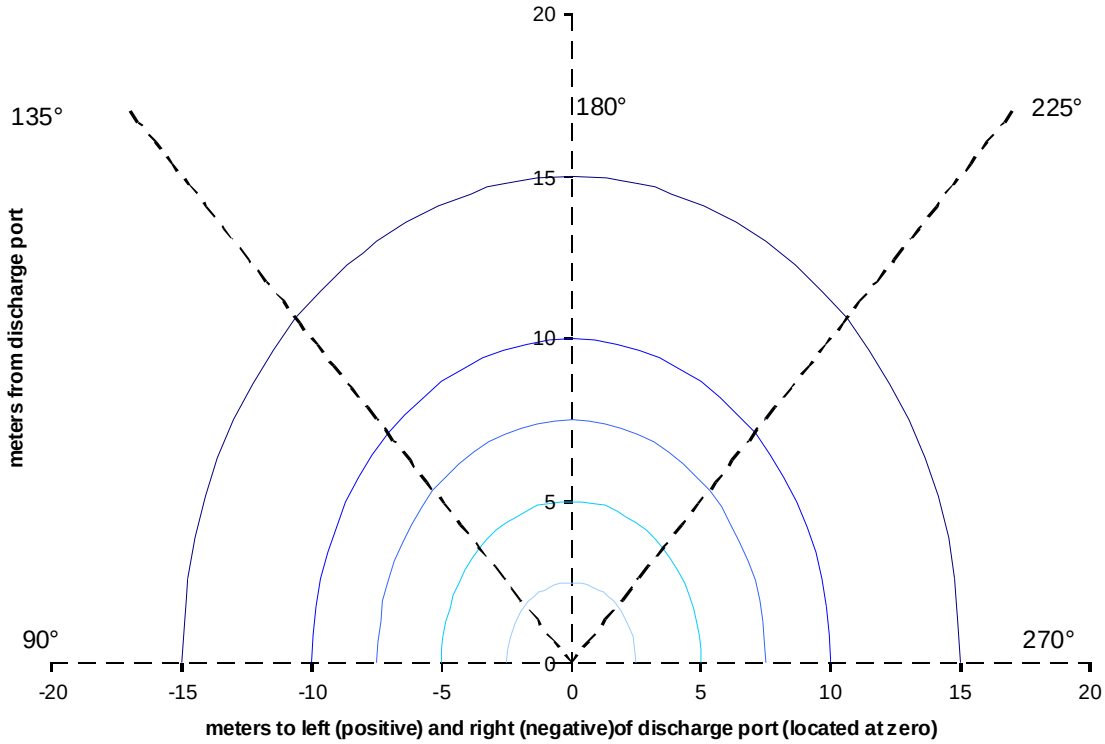

Figure 3-3. Orientation of Arc Transects for Dye Measurements

3.5 Current and Weather Measurements

At least two current meters (S4 current meters, InterOcean Systems, Inc.) were deployed off each cruise vessel to collect current measurements during the dilution studies (in some cases, three meters were used). The meters were deployed from the cruise vessels (to negate current meter motion relative to the vessels), approximately 15 meters away from the discharge port and approximately 3 meters out from the hull (to avoid interference from the vessel's metallic hull with the magnetic sensor of the current meter). The current meters were deployed at depths of 1 and 3 meters (or at depths of 1, 3, and 5 meters if a third current meter was used). Current measurements documented the ambient currents that affected the trajectory and dilution of the plume.

Weather conditions (e.g., air temperature, wind speed, and wind direction) were recorded by OSV *Bold* personnel during the dilution studies.

4. RESULTS

4.1 Discharge Plumes

Uncorrected dye concentration data for all transects are provided in Appendix B (see Section 5.1). In general, it appears that most near-field dilution occurs within 2.5 meters of the discharge port, with the plumes remaining relatively intact to distances of approximately 15 meters. The minimum dye dilution factors discussed in this report are the ratio of the initial dye concentration (i.e., dye concentration prior to discharge from the port) to the maximum dye concentration observed in the plume. The minimum dilution factors observed during arc transects conducted 15 meters from the discharge port ranged from approximately 40 to 90.

The following narratives provide a brief description of a complex dynamic phenomenon. The data collected in this study will be further analyzed by the ADEC to validate previous modeling studies on nearfield dilution of these treated sewage and graywater discharges.

Star Princess. This ship's discharge port was the shallowest of all the sampled cruise vessels (see Table 2-1). The discharge plume was the only one visible from the water surface; it moved along the hull at an angle between 255 and 270° from the discharge port location. Detected dye concentrations ranged up to approximately 57 ppb. It is unknown whether higher concentrations would have been detected if the CTD + SCUFA® array was able to measure dye concentrations near the surface of the water column (see section 5.1). Detected dye concentrations observed along the 270° transect were approximately similar at distances of 5 meters and 7.5 meters from the discharge port, and somewhat lower at a distance of 10 meters; however, the highest concentration of dye was observed on the 255° transect at a distance of 10 meters. EPA did not prepare a profile of arc transect results for the *Star Princess* because arc transects were not performed.

Coral Princess. Discharge from the *Coral Princess* was highly intermittent. During periods of no flow, the shipboard survey team suspended dye injection to minimize dye accumulation in the discharge piping, which could cause spikes and variability in discharge Rhodamine WT dye concentration. As a result, dye concentration data in Appendix B for the *Coral Princess* represent intermittent wastewater discharge with discharge dye concentration variability that is not well characterized. Because of this variability and strong water currents, the discharge plume was difficult to detect. Toward the end of the sampling period, detected plume dye concentrations ranged up to 270 ppb and were highly variable in concentration and in location (as measured both by depth and degrees from the discharge port). EPA did not prepare a profile of arc transect results for the *Coral Princess* due to the highly intermittent nature of the discharge.

Ryndam. The discharge plume was most clearly characterized moving at an angle of 135° from the discharge port. The discharge plume was also detected at angles of 180° and 90°, particularly toward the end of the sampling period. Detected plume dye concentrations ranged from 5 ppb to approximately 20 ppb. During the arc transects, the minimum dilution factor of approximately 34 was observed at 5 meters from the discharge port (note: this dilution factor is based on an estimated initial dye concentration of 700 ppb). Maximum dye concentrations observed during arc transects, at various distances and depths are presented in Figure 4-1. For these transects, a minimum dilution factor of approximately 93 was observed 15 meters from the discharge port.

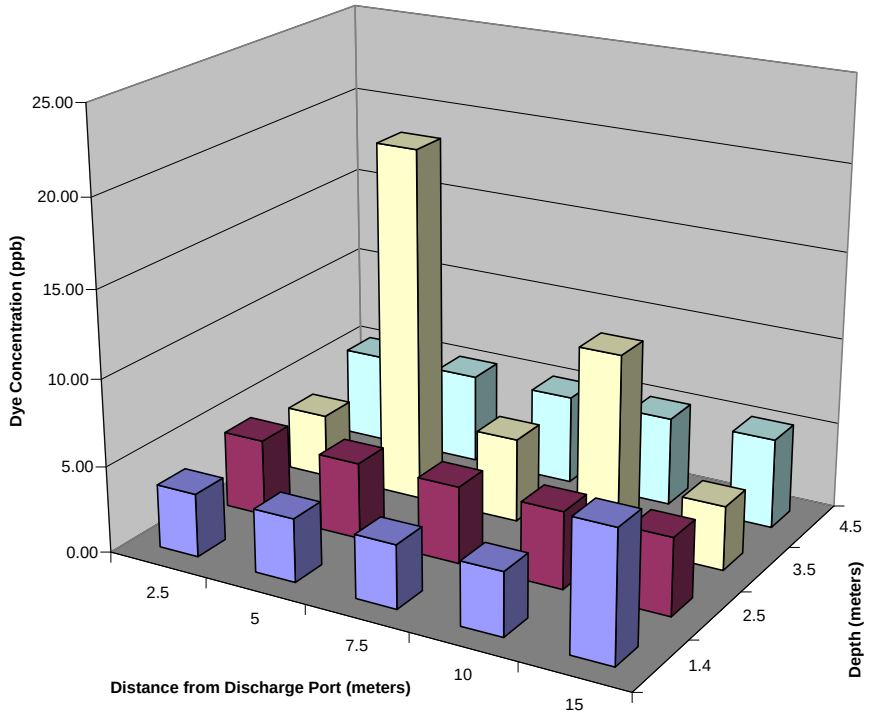

Figure 4-1. Profile of Arc Transect Results for *Ryndam*

Celebrity Millennium. The discharge plume was most clearly characterized moving at angles ranging from 240° to 270° from the discharge port. The discharge plume was observed at depths ranging from 5 to 7 meters. Detected plume dye concentrations ranged up to 47 ppb. During the arc transects, the minimum dilution factor of approximately 11 was observed 2.5 meters from the discharge port. Maximum dye concentrations observed during arc transects, at various distances and depths are presented in Figure 4-2. For these transects, a minimum dilution factor of approximately 39 was observed 15 meters from the discharge port.

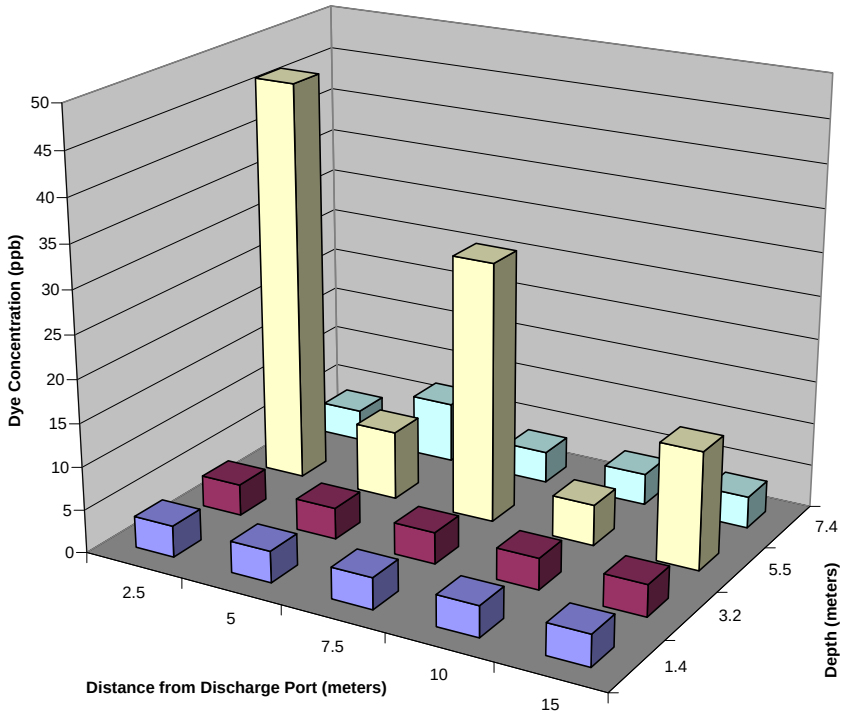

Figure 4-2. Profile of Arc Transect Results for *Celebrity Millennium*

Norwegian Star. The discharge plume was most clearly characterized moving at angles ranging from 250° to 270° from the discharge port. The discharge plume was observed at depths ranging from 3 to 5.5 meters. Detected plume dye concentrations ranged up to approximately 88 ppb. During the arc transects, the minimum dilution factor of approximately 13 was observed 5 meters from the discharge port. Maximum dye concentrations observed during arc transects, at various distances and depths are presented in Figure 4-3. For these transects, a minimum dilution factor of approximately 43 was observed 15 meters from the discharge port.

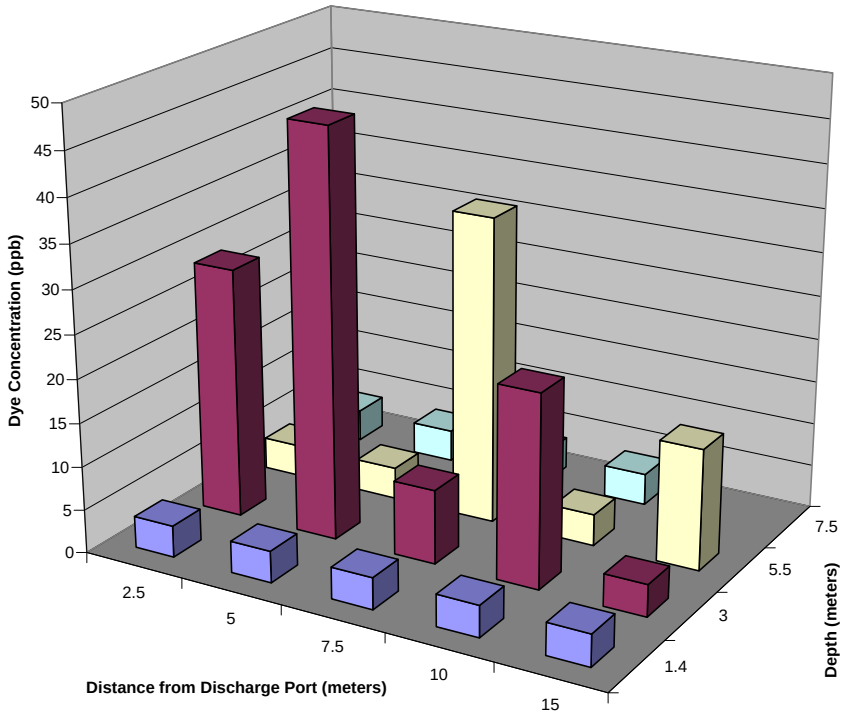

Figure 4-3. Profile of Arc Transect Results for *Norwegian Star*

Volendam. The discharge plume was most clearly characterized moving at angles ranging from 125° to 225°. The discharge plume was generally observed at a depth of 5.3 meters with detected dye concentrations ranging up to approximately 21 ppb. During the arc transects, the minimum dilution factor of approximately 37 was observed 5 meters from the discharge port. Maximum dye concentrations observed during arc transects, at various distances and depths are presented in Figure 4-4. For these transects, a minimum dilution factor of approximately 45 was observed 15 meters from the discharge port.

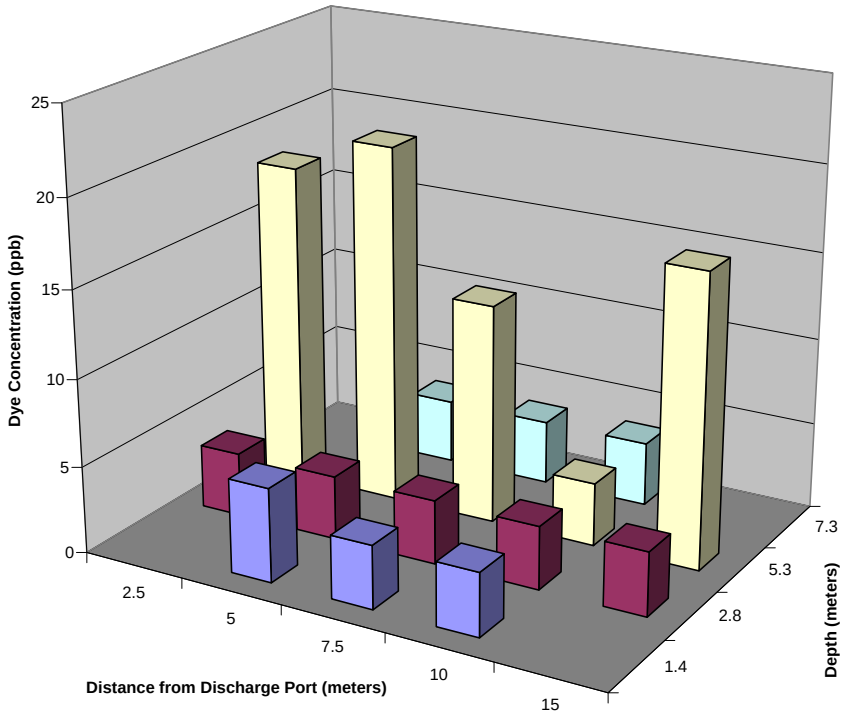

Figure 4-4. Profile of Arc Transect Results for *Volendam*

4.2 Transect Water Quality Data

Data on water temperature, conductivity, depth (of the sensor array), turbidity, and salinity from each transect are provided in Appendix B. Skagway Harbor salinity depth profiles (from the pre-dye transects for most ships) are provided in Appendix C. For all vessels, the halocline appeared to be deeper than the discharge port (see Figures C-1 through C-4 in Appendix C).

4.3 Current Measurements and Weather Data

Current measurements collected during the cruise ship plume dilution study are provided in Appendix D (see Figures D-1 through D-13 in Appendix D). For the polar plots, magnetic north corresponds to 0°. In Skagway, true north is 22.6° east of magnetic north. The heading of all the cruise vessels in this study was 40° east of true north. Therefore, when analyzing the current data, the ship headings were 62.6° east of magnetic north.

The current meters were pre-programmed to begin data collection well before actual deployment from the cruise ships, and the meters continued to collect data until after their retrieval. Current data presented in this report include only the subset of data collected during the cruise ship plume dilution study (see Table 3-1).

National Oceanic and Atmospheric Administration Tide Tables for Skagway for July are provided in Appendix E. These tide tables are provided to supplement and inform the current measurements.

Weather data (air temperature, wind speed, and wind direction) recorded during the cruise ship plume dilution study are provided in Appendix H.

5. DATA QUALITY

Quality assurance/quality control (QA/QC) procedures applicable for this program are outlined in the *Quality Assurance Project Plan for Support for OSV* Bold *Survey of Large Cruise Ship Wastewater Impacts in Alaskan Waters (QAPP)*, which is reproduced in Appendix J. This section provides an assessment of the QAPP project data quality objectives specific to the cruise ship plume dilution study, which were established for the key measurements of the concentration of Rhodamine WT dye in the near-field plume and in the cruise ships discharges. In addition, this section provides a brief quality assurance assessment of non-key measurements.

Trial dilution studies were conducted on the *Celebrity Millennium* on July 7 and on the *Norwegian Star* on July 9 to refine the sample collection and analysis methodologies. Data from these trial studies are not presented in this report. Sampling on the *Celebrity Millennium* and the *Norwegian Star* was repeated on July 15 and July 16, respectively.

5.1 Quality Assurance Assessment of Key Plume Dilution Study Measurements

For the cruise ship plume dilution study, the key measurements identified in the QAPP are the concentration of Rhodamine WT dye in the near-field plume and in the cruise vessel discharge (end-of-pipe). The data quality objectives for these measurements are defined in terms of completeness, accuracy, precision, representativeness, and comparability.

Completeness (Near-Field Plume Dye Concentrations)

Dye concentration data in the near-field plume are complete for all vessels surveyed except the *Star Princess*. The discharge plume for the *Star Princess* was visible at the surface of Skagway Harbor. The CTD + SCUFA® array is designed to take measurements at approximately 1.5 meters of depth and deeper. As a result, data for the *Star Princess* do not characterize the entire plume, but only the portion of the plume deeper than approximately 1.5 meters.

Completeness (Cruise Ship Discharge Dye Concentrations)

Discharge dye concentrations were calculated by multiplying the measured discharge rates by the known feedstock dye concentrations. On three cruise vessels (*Celebrity Millennium*, *Norwegian Star*, and *Volendam*), a SCUFA® fluorescence sensor was installed on the discharge piping to verify dye concentrations. For the other three vessels, the SCUFA® sensor could not be used to verify dye concentrations due to damage sustained during an unannounced emergency generator power drill on one of the ships. When fluorescence data could not be collected, the survey team verified dye discharge by visual observation. Dye concentration was assumed to be the calculated concentration.

Accuracy and Calibration

Dilution series performed for the three SCUFA® fluorometers prior to field testing showed excellent accuracy, with a highly linear response from approximately 5 ppb through 300 ppb. The dilution series and initial trial testing on *Celebrity Millennium* on July 7 revealed that the practical detection limit for the fluorometers was the seawater background signal of

approximately 1.6 ppb (contrary to the detection limit of 0.04 ppb reported by the manufacturer[2]). A calibration curve for the range of 5 to 50 ppb was found to be linear ($R^2 > 0.99$). Actual dye concentrations are obtained using the following expression:

$$C = 0.768*C' + 4$$

where C equals dye concentration and C' is the uncorrected fluorometer response.

In consideration of the loss of two orders of magnitude of SCUFA® sensitivity, the survey team increased the target shipboard dye concentration from the planned 100 ppb to 700 ppb. Consequently, a second calibration curve was prepared for high dye concentrations. For the calibration range of 84 to 660 ppb, the calibration curve was linear ($R^2>0.99$) and fit the following expression:

$$C = 1.02*C' + 9$$

where C equals dye concentration and C' is the uncorrected fluorometer response.

Precision and Representativeness

The QAPP specified collection of duplicate CTD+SCUFA® data using a pair of arrays towed side-by-side from the RIB. Field duplicate sampling using two adjacent CTD+SCUFA® arrays was not performed. The secondary CTD+SCUFA® array was dismantled to provide a SCUFA® fluorometer to replace the damaged shipboard unit.

Comparability (Among Ship Discharge Tests)

The sample collection and analysis methodology was consistent for all cruise ship plume dilution studies. Dilution study transects were generally consistent among ships, with some deviations necessary to account for ship-specific conditions and weather conditions during each test.

Overall Data Quality Assessment

This data quality assessment indicates that the key measurements collected during the cruise ship plume dilution study are of sufficient quality for use in analyzing near-field mixing dynamics of the effluent plumes from stationary cruise ships in Skagway Harbor.

5.2 Quality Assurance Assessment of Non-Key Plume Dilution Study Measurements

Discharge Flow Measurements

Ship discharge flows were measured on all cruise vessels except the *Norwegian Star*. For the *Norwegian Star*, discharge flows were measured only during the set-up period because the meter malfunctioned at the start of the sampling period. Repeated attempts to reinstall the flow

[2] Telephone contact with the manufacturer revealed that the reported detection limit can be achieved only under ideal, laboratory conditions.

meter were unsuccessful. Therefore, *Norwegian Star* discharge dye concentration was measured using a SCUFA® sensor (as it could not be calculated using flow rates).

While discharge flow data were monitored by the shipboard survey team, they were not reliably logged electronically because of a smaller than expected data-logging buffer capacity. For the *Star Princess*, *Coral Princess*, *Ryndam,* and *Celebrity Millennium* sampling events, electronic data logs are available for only the last 7 to 15 minutes of testing. For the *Norwegian Star*, electronic data logs are available for the last 2 hours of testing. For the *Volendam*, electronic data logs are complete for the entire period of testing. Electronically logged discharge flow data were supplemented by field logs taken by the shipboard survey team (see Appendix F).

Two ships, *Ryndam* and *Volendam*, operated flow meters on their discharge. On both of these ships, ultrasonic flow meter measurements closely matched measurements made by these ships' built-in meters.

Current Measurements

Harbor current was measured during all sampling events for all six ships. For two of the six ships tested, current meters were deployed at 1, 3, and 5 meter depths. For the other four ships, current meters were deployed only at 1 and 3 meter depths due to the difficulty of deploying the meters. For one ship (*Norwegian Star*), current was not measured at the 1 meter depth due to water seepage into the connector cover on the meter. Current measurements collected are reasonable, based on their correlation to the location and direction of the detected plume.

Weather Data

Weather conditions (e.g., air temperature, wind speed, and wind direction) were recorded by the OSV *Bold* personnel during measurements of plume dilution, with the exception of dilution measurements collected for the *Coral Princess* on July 11.