Cruise Ship Plume Tracking Survey Report

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1. Introduction

The U. S. Environmental Protection Agency (EPA) is developing a Cruise Ship Discharge Assessment Report in response to a petition the agency received in March 2000. The petition requested that EPA assess and where necessary control discharges from cruise ships. Comments received during public hearings, in 2000, resulted in the EPA agreeing to conduct a survey to assess the discharge plumes resulting from cruise ships, operating in ocean waters off the Florida coast and to compare the results to the Alaska dispersion models.

The EPA conducted a survey to track and quantify the plume dilution and dispersal, offshore Miami, Florida (Figure 1), and within the normal transit lanes for cruise ships operating out of Miami, on August 7-15, 2001. The survey was conducted aboard the U.S. Environmental Protection Agency's Ocean Survey Vessel *Peter W. Anderson* (OSV Anderson). The survey participants along with affiliation and survey responsibility are listed in Table 1. Mobilization for the survey was conducted at the U.S. Coast Guard Base in Miami, Florida on August 7, 8 and 9, 2001.

Table 1. Survey Party and Responsibilities.

Name	Affiliation	Survey Responsibility	Survey Dates
Dave Redford	EPA Headquarters	Chief Scientist	Aug 7-14, 2001
Ken Potts	EPA Headquarters	Work Assignment Manager	Aug 7-14, 2001
Wayne Trulli	Battelle	Battelle Lead Scientist	Aug 7-14, 2001
Bob Mandeville	Battelle	BOSS Operator	Aug 7-14, 2001
Stacy Abramson	Battelle	Sampling Technician	Aug 7-14, 2001
Tim Kaufman	Battelle	Winch operator	Aug 7-14, 2001
Brandy Curtis	Battelle	Sampling technician	Aug 7-14, 2001
Kenwyn George	Alaska DEC	Observer	Aug 10-13, 2001
Bob Howard	EPA Region IV	Observer	Aug 10-13, 2001
Don Kim	AMSEC	Observer	Aug 10-13, 2001
Stan Demo	ICCL	Observer	Aug 10-13, 2001

EPA worked with the International Council of Cruise Lines to identify cruise ships, their location, transit routes and sailing schedules, and to coordinate with the needs of the survey. EPA worked closely with Royal Caribbean Cruise Lines and Carnival Cruise Lines representatives and ship personnel to understand the complexities of identifying holding tanks, and to coordinate the addition of dye to tanks, and the discharge of dye and drogues. The bridge officers from the OSV Anderson and cruise ships also met to discuss protocols of handling the ships while in close proximity of each other.

The dye plumes of four cruise ships were monitored: the *Majesty of the Seas*, the *Explorer of the Seas*, the *Paradise*, and the *Fascination*. The *Majesty of the Seas* and the *Explorer of the Seas* from Royal Caribbean Cruise Lines were monitored on August 10 and 11, respectively; and the

Paradise and *Fascination* from Carnival Cruise Lines were monitored on August 12 and 13, respectively. The tracklines followed during monitoring for each ship are shown in Figure 1.

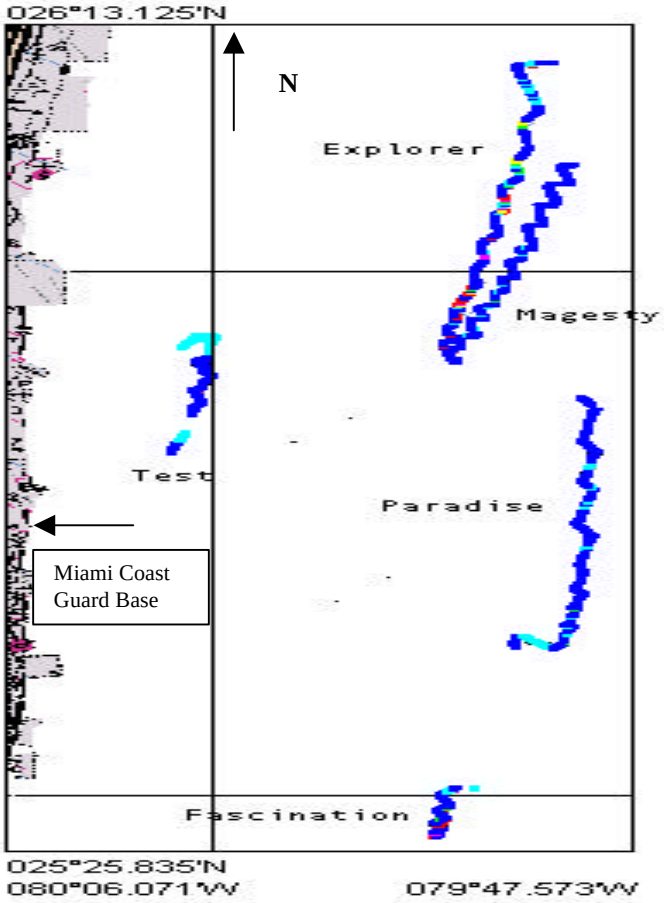


Figure 1. Miami, FL, Offshore Study Area Showing Tracks Through the Plumes of Each of Four Cruise Ships Monitored.

This survey report describes the daily activities of *August 2001 Cruise Ship Plume Tracking Survey*, and provides a synopsis of the observations from the survey. It also provides data that can be used to assess dispersion of cruise ship wastewater discharges, while in transit. A description of the survey methods is provided in Section 2. Survey results are presented in Section 3. Findings and conclusions are discussed in Section 4.

This study finds that dilution of discharges behind cruise ships moving at between 9.1 and 17.4 knots are diluted by a factor of between 200,000:1 and 640,000:1. Measured dilutions are significantly higher than the 40,000:1 initial dilution predicted by a model developed by Colonell et al (2000), suggesting that secondary dilution is an important factor.

2. Methods

The following subsections briefly summarize the methods used during this survey. The combined work/quality assurance project plan (W/QAPP) for *Cruise Ship Sampling* (Battelle 2001)[1] contains additional details on survey sampling methods.

2.1. Vessel Specifications and Test Conditions for Cruise Ships

The vessels provided a range of study platforms in terms of vessel sizes, types, and rates of discharge studied. Table 2 lists each vessel's specifications as they pertain to the study.

2.2. Method Descriptions:

Navigation. Vessel positioning during sampling operations was accomplished using the OSV *Anderson* Differential Global Positioning System (DGPS) interfaced to Battelle's NavSam© navigation system. The DGPS receiver has six dedicated channels and is capable of locking onto six different satellites at one time. To correct the Global Positioning System (GPS) calculations, the DGPS receives correction data from one of the United States Coast Guard DGPS broadcast sites in Florida: Key West, Virginia Key, Cape Canaveral, Macdill AFB, and Egmont Key. This capability ensured strong signal reception, and accurate and reliable positioning with 2-second updates. The DGPS was operated and maintained according to the operator's manual.

A calibration check of the navigation system vs. known benchmarks was conducted twice daily to verify that the system was working properly. The checks were conducted prior to departing the dock and following arrival at the dock during daily operations.

Plume Tracking Using the Battelle Ocean Sampling System. Plume tracking was conducted using the Battelle Ocean Sampling System (BOSS) deployed from the OSV *Anderson*. Three types of plume tracking activities were conducted during the survey: a shakedown survey, four background surveys conducted on each survey day for each of the four ships, and the four plume tracking surveys. Each type of survey is briefly discussed below.

The towfish with *in situ* sensor package (BOSS) was used to conduct all of the plume tracking activities. The sensor package included a conductivity, temperature, depth (CTD) sensor, and a fluorescence sensor (set at 0-5µg/L – referred to as Dye 1). A second fluorescence sensor (set at 0-50µg - referred to as Dye 2), was used in case concentrations exceeded the range of the first sensor. Table 3 lists the field measurements acquired from the BOSS during each monitoring event.

[1] Battelle. 2001. Work/Quality Assurance Project Plan for Cruise Ship Sampling. Prepared for U.S. Environmental Protection Agency Oceans and Coastal Protection Division, Washington, DC. Contract No. 68-C-00-121, Work Assignment 1-23. 33pp+apps.

Table 2. Vessel Specifications and Test Conditions for Cruise Ships.

Most of the data were provided by the cruise lines.

Specification or Test Condition	**Cruise Ship**			
	Majesty	***Explorer***	***Paradise***	***Fascination***
Vessel Specifications				
Length/Beam	268.3m/32.6m	311.13m/38.6m	260.6/31.4	260.6/31.4
Draft to lowest tip of screws	7.50 m	8.80 m	7.75 m	1.5 m
Draft to bottom of ship	7.70 m	8.80 m	7.75 m	7.75 m
Size of tank in study	220 m^3	25.9 m^3	175 m^3	30 m^3
Type of tank	Gray water	Black water	Gray water	Gray water/ laundry
Location of discharge port	N/A	DN 150 FRAME 75-76	Starboard, frame 136	Port side, frame 32
Vertical depth	5.6 m	6.4	6 m	6.35 m
Distance from bow	~172.36 m from forward PP	225 m	146 m at waterline	200.8 m at waterline
Distance from stern	~65.64 m from aft PP	66.6 m	114.6 m at waterline	59.8 m at waterline
Distance from screws	54.25 m	57.6 m	99.8 m	~15.2+m
Distance from keel	1.9 m	2.4 m	55.16 m	28.81 m
Distance from water line	5.6 m	6.4 m	6 m	1.25 m
Size of discharge pipe and through-hull fitting	203 mm	203 mm	200 mm	88.9 mm
Discharge pump rate (rated)	220 m^3/hr	50 m^3/h	50 m^3/hr	50 m^3/hr
Number of propellers	2	3	2	2
Diameter of propellers	4.9 m (4 blades)	5.4 m fixipod 5.6 m azipods	5.2 m Azipods	5.2 m
Direction of propeller rotation (aft view)	CW (port) CC (starboard)	CC (starboard) CW (port) CW (fixipod)	CC (port) CW (starboard)	CC (port) CW (starboard)
Test Conditions				
Vessel speed during test: Speed Over Water (SOW)	17.4 knots	19 knots	15.0 knots (see Survey Chronology)	9.1 knots (see Survey Chronology)
Volume of seawater added to tank	113 m^3 gray water only	16.6 m^3	108 m^3 gray water only	27 m^3 gray/ fresh water
Volume of test solution at discharge Time Zero (T_0)	113 m^3 + 114 L dye (~0.1m^3 dye)	18 m^3 (includes 133 L dye - ~0.1m^3 dye)	108 m^3 + 133L dye (~0.1m^3 dye)	27 m^3 + 137L dye (~0.1m^3 dye)
Date - Time discharge began (T_0)	8/10/01 - 18:44	8/11/01 - 19:43	8/12/01 - 19:00	8/13/01 - 19:15
Time discharge completed (T_{end})	19:41	20:01	19:30	19:35
Volume in tank when discharge completed (T_{end})	7 m^3	1.2 m^3	40 m^3	3 m^3
Volume in tank after 20 min (calculated)	78 m^3	~1.2 m^3	62.6 m^3 **	3 m^3 ***
Number of pumps used to discharge water/dye solution for 20 min.	1 0-20 min 2 20+ min	1	2	1
Discharge rate of pump(s) (rated/actual)	220/112 m^3/hr	50/56 m^3/hr	50/68.0 m^3/hr	50/72 m^3/hr
Amount of dye in tank at T_0	30 gal.	35 gal.	35 gal.	36 gal.

** Calculation: 108 m^3 - 40 m^3 = 68 m^3, and 68 m^3 in 30 min pumping = 2.27 m^3/min, then 2.27 m^3/min * 20 min = 45.4 m^3, and 108 m^3 – 45.4 m^3 = 62.6 m^3.
***Calculation: 27 m^3 - 3 m^3 = 24 m^3, and 24 m^3 in 20 min pumping = 1.2 m^3/min, then 1.2 m^3/min * 20 min = 24 m^3, and 27 m^3 – 24 m^3 = 3 m^3.

Table 3. Summary of Field Instruments Measurements

Parameter	Lab	Units	Instrument
Conductivity	Battelle	Mmhos/cm	OS200 CTD
Temperature	Battelle	°C	OS200 CTD
Pressure	Battelle	M	OS200 CTD
Transmissometry/turbidity	Battelle	m-1	Seatech 20-cm (660nm) (2)/Seapoint RWT Sensor
Bottom depths	*Anderson*	M	Furuno FCV-52
Navigational position	*Anderson*	Degrees	Northstar 942X
Ocean current velocity	Battelle	Cm/sec	RD Instruments ADCP WHM600-I-UG6
Sigma-t	Battelle	no units	OS200 CTD (calculated)
Salinity	Battelle	PSU	OS200 CTD (calculated)
Rhodamine fluorescence	Battelle	µg/L	Seapoint RWT fluorometer

The rhodamine fluorometer measures dye concentrations (ppb) directly. All dye data reported in this document were collected from the Dye 2 sensor (set to measure dye concentrations ranging from 0-50 µg/L). These *in-situ* fluorescence measurements were electronically recorded continuously throughout multiple passes for each plume monitored. All rhodamine dye fluorescence data presented in this report are corrected for temperature.

The station/sample location number, GPS coordinates, date and time, depth of the water column, and any observations associated with the sampling at each sampling location were made in the field survey logbook. Each sample was assigned a unique ID and label by NavSam©, which also electronically stored the field and sensor data. Exceptions are noted in Section 5.

BOSS sensor data were collected continuously during plume tracking activities. The BOSS was deployed approximately 10 ft. off of the port side of the *Anderson* using the boom crane to minimize the impact of the *Anderson's* wake and propellers on the monitoring activities.

Shakedown Survey. A shakedown survey was conducted to determine whether the *in-situ* fluorescence sensors were able to detect dye concentrations of <10µg/L. The *Anderson* transited to a location in the ocean in the vicinity of the study area. Dye was carefully added directly into the ocean (less than 0.5 gal.) via a funnel and a long Tygon tube as the *Anderson* transited at a speed of approximately 5 kts. After the dye addition, the *Anderson* was maneuvered to run a transect through the dye. When the *in-situ* dye fluorescence instruments registered faint spikes indicating that dye was detected by both sensors, the *Anderson* headed back to Miami to make preparations for tracking the *Majesty* plume on the following day.

Background Transect Monitoring and Sampling. A single background transect was conducted on each survey day in the vicinity of the rendezvous point before the respective cruise ship arrived on station (Figures 2-5). BOSS sensor data was collected continuously along transects while on station waiting for the cruise ship. Samples for dye sensor calibration were collected at various depths ranging from 2 to 12 m at locations along the length of the transect.

Plume Transect Monitoring and Sampling. The transect configuration and the sampling locations along each plume transect were different for each cruise ship. Each configuration varied based on how the dye plume behaved in the existing currents after the dye was released. During the release of the dye from each cruise ship, drogued buoys equipped with lights and radar reflectors were released at approximately two-minute intervals (beginning when dye release was initiated) to permit easier tracking of the sub-surface plume. The drogues for each buoy were tethered ~2 m below the bottom of its associated buoy so that any existing surface currents would carry the drogues along with the targeted plume. Buoys were used to aid in tracking the plume. The deployment and retrieval locations were recorded by hand for all vessels except the *Majesty*.

After the cruise ship deployed the first buoy prior to passing the *Anderson* indicating the beginning of dye release, the *Anderson* began maneuvering to enter the plume on a track nearly perpendicular to the cruise ship's heading. The first transect (considered to be the initial dilution) was conducted at the surface (approximately 2 m deep). Samples for dye were collected on this first transect at the surface for every ship. The second, third, and fourth transects were with few exceptions taken at 5m, 8m, and 12m, respectively. In general, the dye samples were taken along these transects as well. As time progressed, transect depths and sampling locations were determined at the discretion of the EPA Chief Scientist (see Sampling Log Data in Appendix B). Table 4 shows the number of background and in-plume transects conducted for each cruise ship and the number of dye samples collected from locations along the selected transects. Additionally, the holding tanks (spiked with the Rhodamine dye) of each monitored cruise ship were sampled to determine actual dye concentration in the tanks prior to discharge. The numbers of samples collected from these tanks are also shown in Table 4.

Table 4. Numbers of Samples Collected and Plume Tracking Transects Completed.

Cruise Ship	Number of Plume Transects	Numbers of Discrete Samples		
		Cruise Ship Samples	Background Discrete Samples	Plume Discrete Samples
		Rhodamine Dye	Rhodamine Dye	Rhodamine Dye
Majesty	23	4*	5	2
Explorer	19	5	5	5
Paradise	17	5	5	8**
Fascination	7	5	5	9**
Survey Total	66	19	20	24

*First sample collected before T=0. Not included in calculations.
**Additional samples were collected (only five samples were planned for each transect).

Average values of depth and dye concentration were taken along each transect for each cruise ship from the point where dye values exceeded background levels until they returned to background levels. Plume width measurements were also made using the same points for obtaining average depth and dye concentrations.

Additional samples, above the five planned dye samples, were taken during monitoring operations for the *Paradise* and *Fascination*.

Upon survey completion, the samples were shipped in coolers containing ice to Battelle for final analysis. Before shipping, the sample custody forms were completed and placed in a sealed Ziploc bag that was taped to the inside of the cooler lid. The Battelle Field Custodian, Mr. Tim Kaufman, shipped *in-situ* plume dye samples from Miami and received them at Battelle. He also received sample shipments from the cruise lines for samples collected aboard the cruise ships.

Sample Storage Conditions. Discrete rhodamine dye samples collected aboard the cruise ships were stored chilled at ~ 4ºC. Each cruise ship was provided a shipping cooler and given instructions to store and ship samples on ice. Additional sample storage conditions are presented in Table 5.

Table 5. Analyte, Sampling Method, Volume, Preservation, and Holding Times.

Analyte (Analytical Laboratory)[(a)]	Matrix	Method	Sample Volume	Container Type	Preservation	Holding Time
Laboratory Analyses						
Rhodamine dye (Battelle)	Water	Seapoint RWT Sensor	500 mL	Polyethylene plastic	Cool, ~ 4°C	undetermined
Field Analyses						
Temperature (BDO)	Water	OS200 CTD	NA	NA	NA	*In situ*
Depth (BDO)	Water	OS200 CTD	NA	NA	NA	*In situ*
Transmissometry/ Turbidity (BDO)	Water	Seatech 20-cm (660nm)	NA	NA	NA	*In situ*
Conductivity (BDO)	Water	OS200 CTD	NA	NA	NA	*In situ*

(a) BDO: Battelle Duxbury Operations
NA = Not applicable.

Acoustic Doppler Profiles. Current data from an acoustic Doppler current profiler (ADCP) on board Royal Caribbean Cruise Line's *Explorer* was obtained from NOAA. This data was collected during transit through the site during the plume tracking survey on August 11.

3. Survey Results and Discussion

All plume tracking and sampling operations were successfully completed over the targeted 4-day period (spanning August 10-14) during which four separate cruise ship discharge plumes were continuously monitored and sampled. Numbers of transects conducted and samples collected are presented in Table 4.

Drogues. The initial and final locations for the drogues are shown in Appendix A and listed in Table 6. The figures in Appendix A indicate that the drogues drifted almost due north at an average speed of 7 Km/Hr and distances ranging from 12 to 20 km for the *Fascination* to 30 to 34 km for the *Explorer* and *Paradise* over the three to five hour sampling periods. The fact that the relative positions of the drogues remained the same indicates that the plumes did not break apart in this time frame as the Florida Current was carrying them northward.

Table 6. Locations of Buoy Deployments from Cruise Ships and Retrieval by *Anderson* During Each Plume Tracking Event.

Cruise Ship	Begin Date	Buoy	Activity	Time (24-h)	Latitude (N)	Longitude (W)
Majesty	08-10-01	No data collected				
		1	Deploy	1943	25°55.697	79°52.697
			Retrieve	Not recovered		
		2	Deploy	1945	26°13.080	79°52.697
			Retrieve	0030	26°13.35	79°51.03
		3	Deploy	1946	25°55.5	79°52.8
			Retrieve	0040	26°12.950	79°51.795
		4	Deploy	1948	25°55.9	79°51.5
			Retrieve	0050	26°12.470	79°52.424
		5	Deploy	1950	25°56.405	79°50.724
Explorer	08-11-01		Retrieve	0058	26°11.989	79°52.993
		1	Deploy	1859	25°38.5	79°51.4
			Retrieve	2350	25°52.8	79°50.0
		2	Deploy	1901	25°38.1	79°50.9
			Retrieve	0000	25°53.8	79°50.7
		3	Deploy	1903	25°37.6	79°50.6
			Retrieve	0010	25°54.1	79°51.6
		4	Deploy	1905	25°37.3	79°50.2
			Retrieve	0020	25°55.2	79°52.3
		5	Deploy	1907	25°36.8	79°49.7
Paradise	08-12-01		Retrieve	0027	25°56.3	79°53.1
		1	Deploy	1910	25°26.70	79°53.55
			Retrieve	2138	25°26.77	79°51.9
		2	Deploy	1914	25°26.39	79°53.39
			Retrieve	2130	25°35.4	79°52.0
		3	Deploy	1916	25°26.09	79°53.30
			Retrieve	2221	25°34.5	79°52.2
		4	Deploy	1918	25°26.81	79°59.37
			Retrieve	2112	25°33.5	79°52.6
		5	Deploy	1921	25°27.09	79°53.34
Fascination	08-13-01		Retrieve	2104	25°32.7	79°52.6

[1]Cruise ship time, position, and activity

The order of deployment vs. recovery did reverse during monitoring of activities for both the *Explorer* and *Paradise*. Since the buoys were not labeled prior to deployment, the order of recovery may have been recorded incorrectly. Otherwise the local currents would have to be highly variable which is not evident from the current data provided by NOAA (Figure 6).

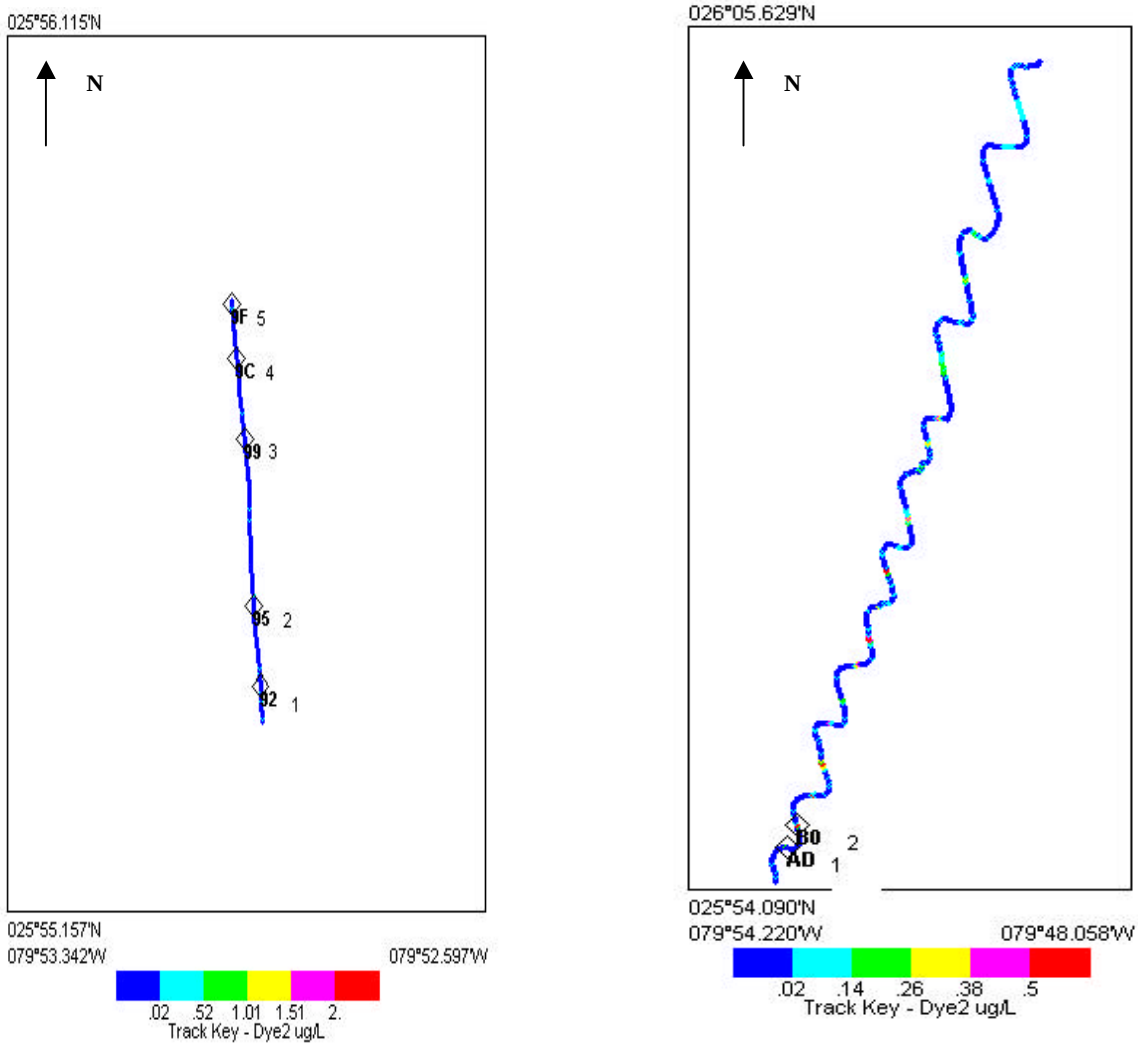
Field Data. All field data (date, time, sampling coordinates, bathymetry, and sample depth) associated with the collection of discrete samples during this survey are presented Appendix B.

Plume Transects, Tracks, and Dye Data. Maps showing the background and survey tracks for each set of plume-tracking events are shown in Figures 2 through 5. Appendix C presents survey tracks and depths for each plume survey. The transect lines are color coded to indicate relative amount of fluorescence and depth of the sensor during a particular transect.

Initial dye concentrations varied considerably depending on the ship and tank specifications at the time of discharge. Table 7 presents several measurements taken during monitoring activities along multiple transects for each cruise ship plume.

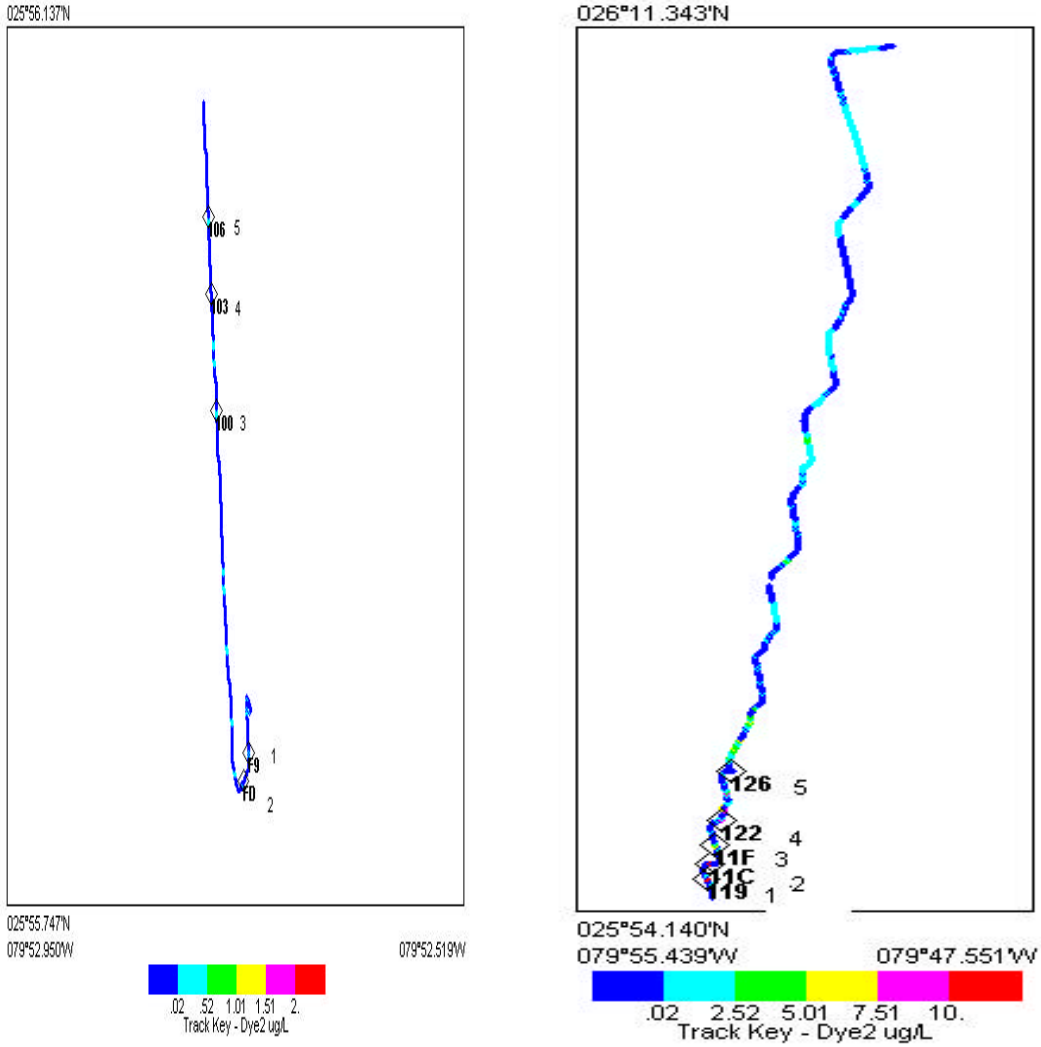
The *Majesty* and *Paradise* discharges exhibited the lowest initial average concentrations of <0.5µg/L. The *Explorer* had the highest initial average concentration exceeding 5µg/L with a maximum of > 36µg/L. The *Fascination* had the second initial highest average concentration >3µg/L with maximum >9µg/L (Table 7).

Time Series Plots and Scatter Plots. Time series plots of dye fluorescence/depth are presented in Appendix D. These plots show the time line of the entire plume survey for each cruise ship and the spikes in dye fluorescence and the transect depth at which the spikes occurred. Appendix E presents the scatter plots of dye fluorescence versus depth. In these plots, the extent of the dye plume relative to depth is evident. These plots were prepared by combining all data files and represent dye concentrations above background levels (0.02 µg/L). All four cruise-ship plumes exhibited high dye concentrations in the surface waters. However for the *Majesty* and *Paradise,* the dye plumes are most concentrated between 5 and 10m, but both plumes penetrate the water column to a depth of approximately 18m. The dye plume of the *Explorer* is very concentrated at the surface and penetrates the water column no deeper than 10 or 12m, possibly because of the propulsion configuration of that vessel. The pattern of the dye-plume scatter plot for the *Fascination* is between the pattern exhibited by the plumes of the *Paradise* and *Explorer*.



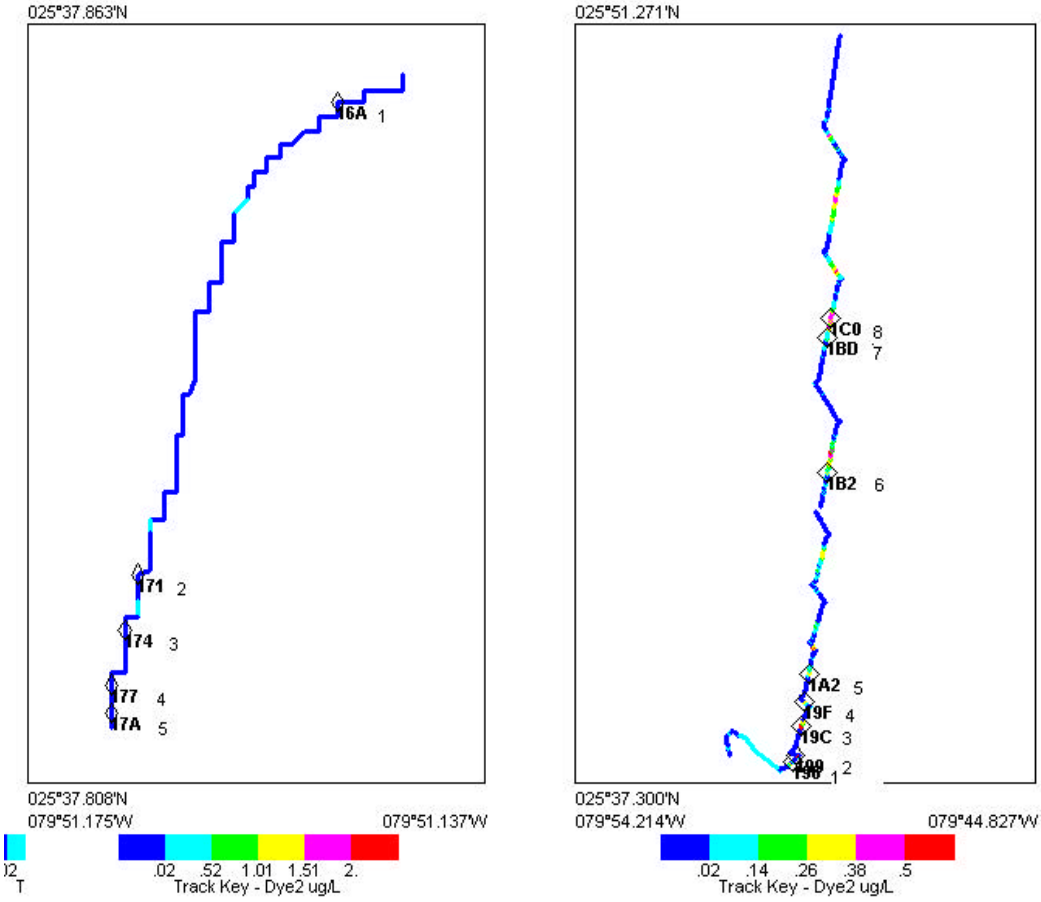
BACKGROUND TRANSECT **IN-PLUME TRANSECTS**

Figure 2. Background and Plume Tracking Transects and Sampling Locations for M/S *Majesty*, August 10, 2001.
(Current had an average speed of ~ 7 Km/ Hr)



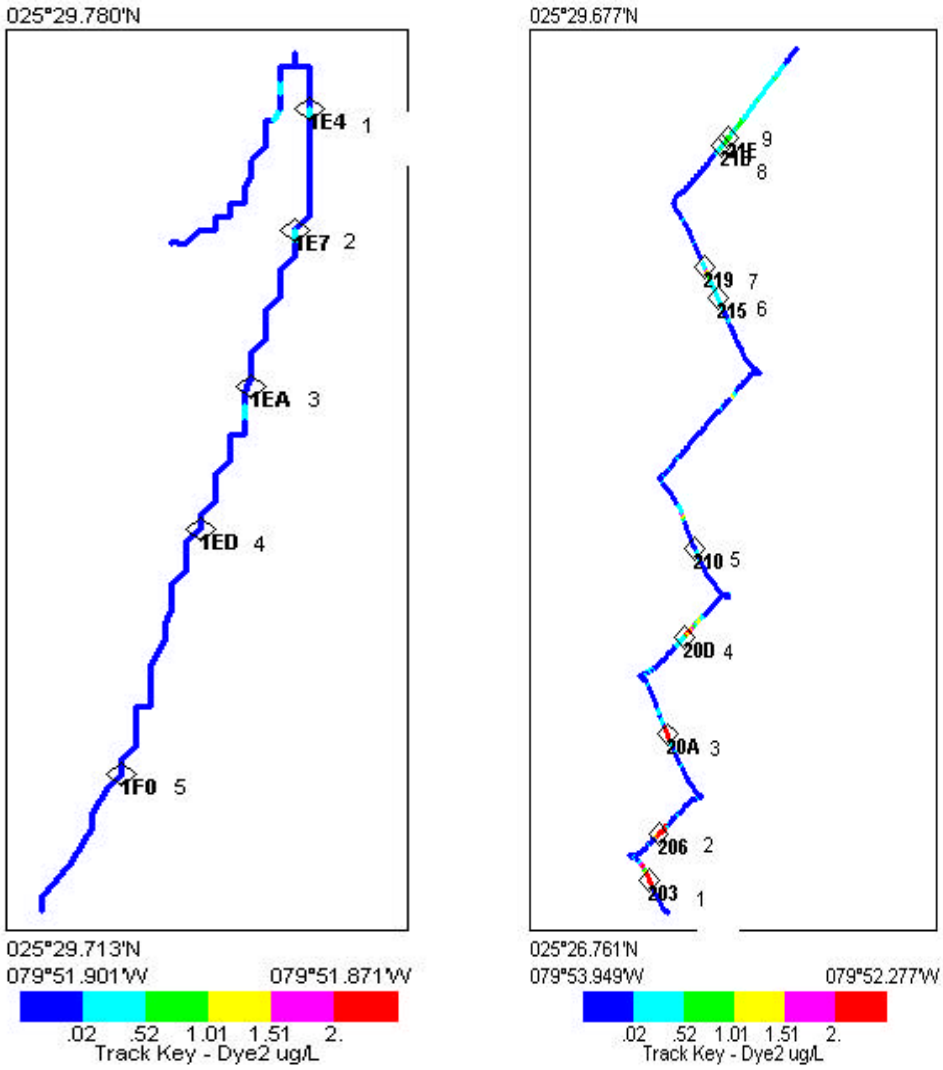
Background Transect **In-plume Transects**

Figure 3. Background and Plume Tracking Transects and Sampling Locations for M/S *Explorer*, August 11, 2001.
(Current had an average speed of ~ 7 Km/ Hr)



Background Transect **In-plume Transects**

Figure 4. Background and Plume Tracking Transects and Sampling Locations for M/S *Paradise*, August 12, 2001.
(Current had an average speed of ~ 7 Km/ Hr)



Background Transect **In-plume Transects**

Figure 5. Background and Plume Tracking Transects and Sampling Locations for M/S *Fascination*, August 13, 2001.
(Current had an average speed of ~ 7 Km/ Hr)

ADCP Data from the M/S Explorer.
Figure 6 shows the current profile structure in the depths ranging from 14 to 44 meters over a four-hour period. These data are provided by the NOAA office located in Miami, Florida. The top segment of Figure 6 shows the depth range from 0 to -44m and the number of pings (ensemble) over time from 0 to ~4.5 hours. The middle and bottom segments of the figure show the direction and magnitude of the currents over the same time period (0 to ~4.5 hours). The date that the data were collected is 8/11/01 (shown as 01/08/11 on the figure); the same day the *Explorer* plume was monitored. The time period of data collection ranged from 22:17 to 02:42 GMT (17:17 to 21:42 EDT) (within the time frame of the plume tracking survey).

The data were taken in 10-meter bins. A bin is a slice of the water column. In this case each slice is 10 meters thick. The top 4 bins are shown (middle and bottom segment of Figure 6): bin 001 (light blue) is centered at -14m, bin 002 (dark blue) is centered at -24m, bin 003 (green) is centered at -34m, and bin 004 (red) is centered at -44m. The course followed by the *Explorer* takes it through the study area and across the Florida Current. The coordinates of the segment extend from 25.78 N latitude, 80.18 W longitude to 26.28N latitude, 78.95 W longitude.

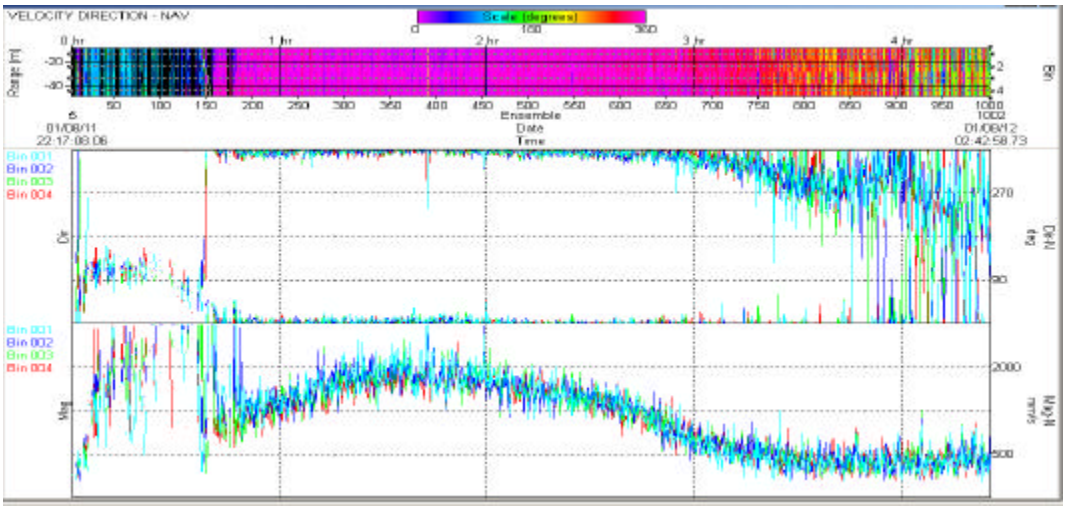


Figure 6. Current Profile Data Taken Aboard the *Explorer* and Provided by the NOAA Office in Miami, Fl

The currents for all depth ranges (bins 001 through 004) are primarily south to north with magnitudes in the range from slightly under 0.5 m/s (~1 Kt.) to nearly 2 m/s (~4 kts.). The currents for all depths match at each location. If shear is present, the direction of one or more of the bins would deviate from the others. This does not occur and currents seem to be uniform over the depths of interest.

Discrete Dye Data. Appendix F contains all the dye data gathered from the discrete samples collected in the cruise ship plumes and collected from the cruise ship tanks. Table F-1 provides

measurements for all samples collected in the cruise ship plumes aboard the *Anderson*. Table F-2 shows discrete sample data collected from the specified cruise ship tanks. It also provides the amount of dye added to the tanks as well as the average measured dye concentrations based on measurements of dye fluorescence from discrete tank samples taken for each cruise ship.

Plume Dilution. Dye concentrations after discharge were measured above background behind every plume. Measured concentrations were lower than calculated concentrations (see Appendix H) except for the *Explorer* and *Paradise*, indicating that initial dilutions are greater than anticipated. Initial dye dilution estimates both calculated and measured were made after discharge. These estimates exceeded dilutions of 100,000:1 and in some cases exceeded 600,000:1 (Table 8 and Appendix G). The calculated estimates were made from tank dye concentration calculations and plume volume estimates based on length, width, and depth of the plume at T=0. The measured estimates are based on fluorescense measurements from tank samples and direct plume measurements (Table 8). In general, dye concentrations generally decreased over time and with depth (Table 7).

Table 7. Average Dye Concentrations in Each Transect for Each Cruise Ship.

Pass	Date	Time	Depth of tow (m)		Estimated Plume Width (m)	Dye Concentration (µg/L)			Filename
			Average	Std. Dev.		Average	Maximum	Std. Dev.	
Cruise Ship: *Majesty*									
1	10-Aug-01	18:48	1.92	0.09	66	0.35	1.08	0.37	W23PT059-00137.Pat
2	10-Aug-01	18:53	5.07	0.06	26	0.42	0.86	0.32	W23PT059-00256.Pat
3	10-Aug-01	18:58	7.89	0.05	75	0.31	1.10	0.36	W23PT059-00401.Pat
4	10-Aug-01	19:04	6.67	5.51	66	0.29	0.93	0.27	W23PT059-00553.Pat
5	10-Aug-01	19:14	2.24	0.08	137	0.20	0.62	0.16	W23PT060-00049.Pat
6	10-Aug-01	19:20	5.11	0.19	37	0.18	0.36	0.11	W23PT060-00190.Pat
7	10-Aug-01	19:27	8.73	0.08	125	0.26	0.51	0.17	W23PT060-00378.Pat
8	10-Aug-01	19:32	11.77	7.80	66	0.29	1.22	0.39	W23PT060-00503.Pat
9	10-Aug-01	19:40	3.40	1.67	300	0.11	1.13	0.23	W23PT060-00708.Pat
10	10-Aug-01	19:48	2.12	0.03	48	0.37	0.72	0.25	W23PT060-00925.Pat
11	10-Aug-01	19:54	5.19	0.02	95	0.27	1.07	0.36	W23PT060-01084.Pat
12	10-Aug-01	20:00	8.33	0.16	76	0.18	0.67	0.17	W23PT060-01230.Pat
13	10-Aug-01	20:11	6.82	7.68	124	0.07	0.34	0.07	W23PT061-00206.Pat
14	10-Aug-01	20:18	2.07	0.03	35	0.19	0.36	0.13	W23PT061-00393.Pat
15	10-Aug-01	20:23	4.38	0.04	92	0.39	0.98	0.30	W23PT061-00528.Pat
16	10-Aug-01	20:32	8.88	0.08	114	0.12	0.25	0.07	W23PT062-00129.Pat
17	10-Aug-01	20:45	10.38	0.06	67	0.21	0.61	0.21	W23PT062-00462.Pat
18	10-Aug-01	20:53	12.03	0.03	40	0.18	0.40	0.12	W23PT062-00661.Pat
19	10-Aug-01	21:01	14.26	0.06	111	0.09	0.29	0.08	W23PT062-00888.Pat
20	10-Aug-01	21:12	17.41	0.07	30	0.04	0.07	0.02	W23PT063-00001.Pat
21	10-Aug-01	21:21	2.17	0.06	298	0.06	0.15	0.03	W23PT063-00241.Pat
22	10-Aug-01	21:31	5.28	0.02	124	0.06	0.10	0.03	W23PT063-00498.Pat
23	10-Aug-01	21:39	8.82	0.17	202	0.02	0.10	0.02	W23PT063-00709.Pat
Cruise Ship: *Explorer*									
1	11-Aug-01	19:44	1.95	0.11	147	5.13	36.15	10.02	W23PT087-00080.Pat
2	11-Aug-01	19:48	4.04	0.83	157	3.08	17.56	5.06	W23PT087-00176.Pat
3	11-Aug-01	19:54	7.54	0.22	86	3.02	9.81	3.20	W23PT087-00339.Pat

Pass	Date	Time	Depth of tow (m)		Estimated Plume Width (m)	Dye Concentration (µg/L)			Filename
			Average	Std. Dev.		Average	Maximum	Std. Dev.	
4	11-Aug-01	20:01	5.35	6.61	144	1.93	10.77	3.19	W23PT087-00506.Pat
5	11-Aug-01	20:07	4.05	4.18	53	4.30	8.89	3.62	W23PT087-00662.Pat
6	11-Aug-01	20:11	2.24	0.03	59	5.46	20.79	6.99	W23PT087-00769.Pat
7	11-Aug-01	20:22	2.51	0.38	69	0.85	3.56	1.17	W23PT088-00207.Pat
8	11-Aug-01	20:25	1.66	1.61	279	2.98	8.54	1.85	W23PT089-00001.Pat
9	11-Aug-01	20:30	3.89	3.35	293	2.56	8.07	2.49	W23PT089-00152.Pat
10	11-Aug-01	21:02	2.59	0.10	67	0.56	2.01	0.58	W23PT089-00972.Pat
11	11-Aug-01	21:05	2.84	0.06	48	2.11	3.59	0.76	W23PT090-00001.Pat
12	11-Aug-01	21:19	6.82	0.57	102	2.28	4.27	1.29	W23PT091-00199.Pat
13	11-Aug-01	21:42	3.98	3.61	119	1.19	4.86	0.94	W23PT092-00198.Pat
14	11-Aug-01	22:05	2.29	0.05	104	1.69	3.08	0.93	W23PT093-00194.Pat
15	11-Aug-01	22:08	2.29	0.06	122	0.50	0.82	0.18	W23PT094-00001.Pat
16	11-Aug-01	22:20	4.58	3.11	68	0.68	1.54	0.55	W23PT095-00133.Pat
17	11-Aug-01	23:00	1.78	0.08	125	1.40	1.94	0.26	W23PT096-00001.Pat
18	11-Aug-01	23:26	5.03	0.04	574	0.38	1.88	0.24	W23PT097-00421.Pat
19	11-Aug-01	23:54	1.87	1.06	909	0.36	1.12	0.24	W23PT098Z-00196.pat
Cruise Ship: *Paradise*									
1	12-Aug-01	19:19	2.11	0.07	182	0.08	0.42	0.10	W23PT119-00066.Pat
2	12-Aug-01	19:24	8.40	0.13	76	0.42	1.28	0.47	W23PT119-00199.Pat
3	12-Aug-01	19:34	9.66	1.09	93	0.41	0.96	0.31	W23PT120-00225.Pat
4	12-Aug-01	19:43	12.62	0.24	57	0.17	0.48	0.15	W23PT120-00457.Pat
5	12-Aug-01	19:54	13.63	0.20	84	0.14	0.34	0.09	W23PT120-00737.Pat
6	12-Aug-01	20:04	4.61	0.50	143	0.39	1.31	0.38	W23PT121-00084.Pat
7	12-Aug-01	20:12	15.54	0.47	109	0.08	0.25	0.06	W23PT122-00040.Pat
8	12-Aug-01	20:26	17.93	0.28	64	0.09	0.31	0.08	W23PT122-00392.Pat
9	12-Aug-01	20:34	2.11	0.12	274	0.12	0.38	0.11	W23PT122-00595.Pat
10	12-Aug-01	20:44	16.28	7.12	296	0.02	0.37	0.03	W23PT123.Pat
11	12-Aug-01	21:04	5.11	0.14	305	0.21	0.62	0.15	W23PT125-00104.Pat
12	12-Aug-01	21:16	15.23	6.39	580	0.01	0.11	0.01	W23PT126.Pat
13	12-Aug-01	21:48	7.97	0.06	341	0.21	0.67	0.17	W23PT128-00165.Pat
14	12-Aug-01	22:05	2.07	0.21	455	0.21	0.56	0.15	W23PT129-00090.Pat
15	12-Aug-01	22:23	5.20	0.31	210	0.18	0.36	0.11	W23PT130-00081.Pat
16	12-Aug-01	22:30	5.06	0.52	135	0.22	0.47	0.13	W23PT131-00001.Pat
17	12-Aug-01	22:44	8.16	0.26	480	0.11	0.50	0.12	W23PT131-00365.Pat
Cruise Ship: *Fascination*									
1	13-Aug-01	19:29	2.30	0.13	88	3.40	8.65	2.66	W23PT149-00042.Pat
2	13-Aug-01	19:34	4.70	0.07	84	3.80	8.52	2.58	W23PT149-00188.Pat
3	13-Aug-01	19:42	8.23	0.11	87	2.27	9.40	3.12	W23PT149-00390.Pat
4	13-Aug-01	19:51	12.07	0.17	189	1.08	4.89	1.22	W23PT149-00625.Pat
5	13-Aug-01	20:02	7.53	5.88	54	0.31	2.74	0.67	W23PT149-00896.Pat
6	13-Aug-01	20:20	2.52	0.12	174	0.30	1.80	0.45	W23PT150-00168.Pat
7	13-Aug-01	20:34	8.35	0.17	471	0.36	0.94	0.20	W23PT151-00245.Pat

Table 8. Calculated and Measured Dye Concentrations and Dilutions for Each of the Four Cruise Ships.

	Parameter	Vessel			
		Majesty	***Explorer***	***Paradise***	***Fascination***
Calculated Values	Dye - v (L)/ wt.(kg)	114/22.6	133/26.4	133/26.4	137/27.1
	Volume of water + dye in tank (L)	113,114	18,300	108,133	27,137
	Tank Concentration (g/L)	0.1998	1.443	0.244	0.999
	Dye discharged (kg)	21,201	24,669	16,635	24103
	Calculated Plume Volume (L)	36,302,904,000	15,517,320,000	45,503,640,000	6,172,100,000
	Calculated plume concentration (g/L)	5.84E-07	1.59E-06	3.66E-07	3.91E-06
	Calculated Dilution	**342,123:1**	**907,547:1**	**666,667:1**	**255,499:1**
Measured Values	Measured Tank Concentration (g/L)	0.13,512	1.002	0.2704	0.9806
	Measured Plume Concentration (g/L)	3.50E-07	5.13E-06	4.20E-07	3.40E-06
	Measured Dilution	**386057:1**	**195,322:1**	**643,810:1**	**288,412:1**

4. Findings and Conclusions

The August 2001 plume tracking survey was designed to provide field data on the cruise ship discharge (effluent) plume characteristics in offshore waters, and provide information on whether or not the cruise ship blackwater or graywater discharge-plumes behave as predicted by a model developed for Alaska waters (Colonell *et al*. 2000)[2].

Based on the Alaska model, effluent discharges from cruise ships were expected to undergo an initial dilution of approximately 40,000:1. Colonell *et al*. (2000)[2] defines initial dilution as the physical mixing of a relatively small and moving discharge entering the water body and secondary dilutions as caused by mixing by the ship propellers. In this plume and tracking report, initial and secondary are not distinguished, but are called initial dilution.

The following findings for each ship were:

M/S Majesty

Calculated dilution: 342,000:1
Measured dilution: 386,000:1

M/S Explorer

Calculated dilution: 908,000:1
Measured dilution: 195,000:1

[2] Colonell, JM, SV Smith, and RB Spies. 2000. Cruise Ship Wastewater Discharge into Alaskan Coastal Waters. Alaska SeaLife Center Technical Report Number 2000-01. 48pp.

M/S Paradise

Calculated dilution: 667,000:1
Measured dilution: 643,000:1

M/S Fascination

Calculated dilution: 255,000:1
Measured dilution: 288,000:1

This survey indicates that discharges from cruise ships undergo a dilution that is much greater than the initial dilution predicted by a model developed by Collonel et al (2000)[2]. Measured dilutions ranged from 195,000 : 1 to 666,000 :1. This indicates that secondary dilution, as the effluent passes through the propellers is an important factor when considering the ambient concentrations of discharge effluents. The effluent will undergo a dramatic and rapid dilution after mixing with ambient water in the prop wash.

In this study, the observed dilution is unlikely to have been influenced by shear currents. The use of surface drogues allowed the OSV Anderson to maintain position with the dye plume as it moved northward in the Florida current. The drogues maintained a relative position during their drift, which indicates that the plume was not exposed to highly variable currents. The acoustic Doppler current profiler data, obtained from the *Majesty*, also indicates that the plumes did not encounter shear or variability in the current.

5. References

Battelle. 2001. Work/Quality Assurance Project Plan for Cruise Ship Sampling. Prepared for U.S. Environmental Protection Agency Oceans and Coastal Protection Division, Washington, DC. Contract NO. 68-C-00-121, Work Assignment 1-23.

Battelle. 2001a. Survey Plan for Cruise Ship Sampling. Prepared for U.S. Environmental Protection Agency Oceans and Coastal Protection Division, Washington, DC. Contract NO. 68-C-00-121, Work Assignment 1-23.

Colonell, JM, SV Smith, and RB Spies. 2000. Cruise Ship Wastewater Discharge into Alaskan Coastal Waters. Alaska SeaLife Center Technical Report Number 2000-01. 4

APPENDIX A

DRIFTER TRACKS FOR THREE OF THE FOUR CRUISE SHIPS MONITORED

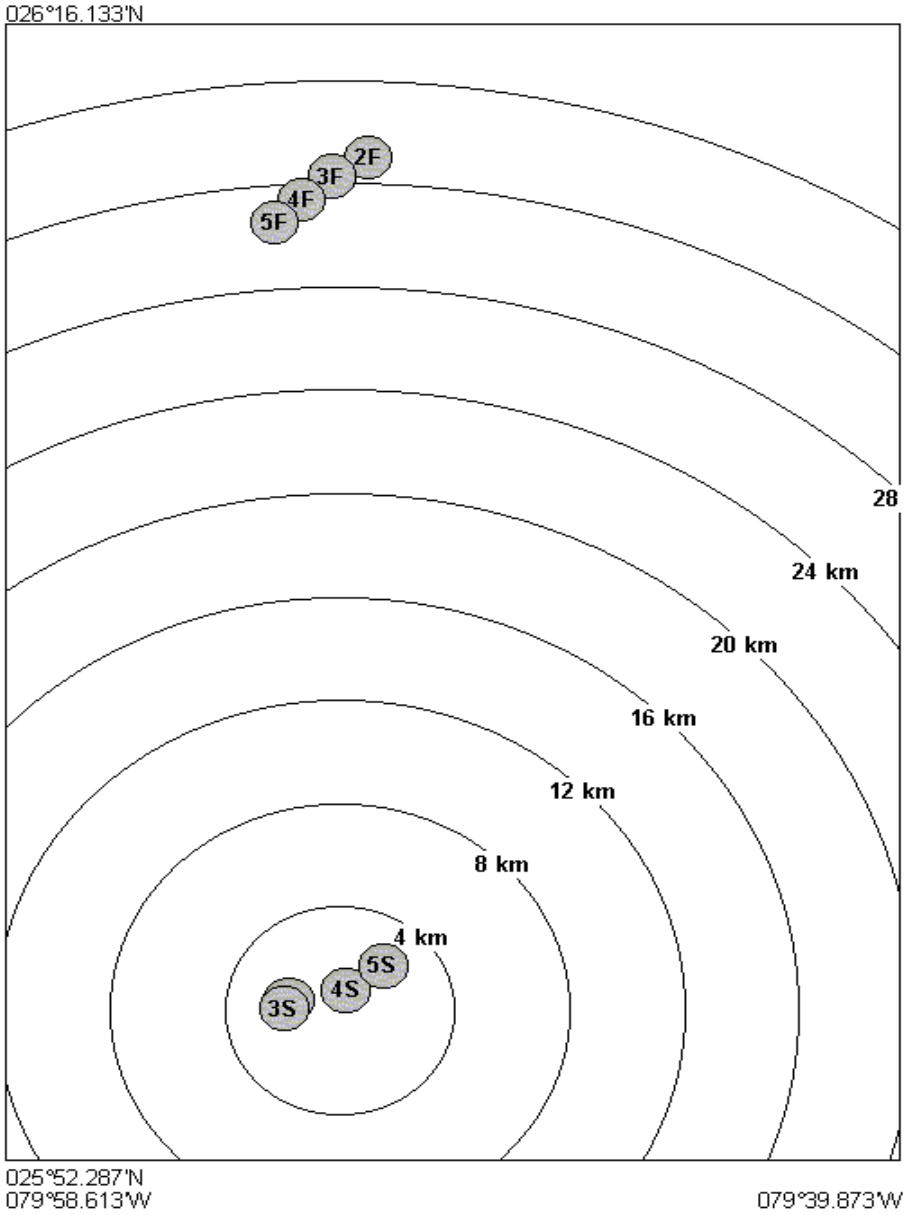


Figure A -1. *Explorer* Drifter Tracks (S -Start and F -Finish) for Set of Five Drifters Deployed and Recovered during the Miami Plume Tracking Survey.

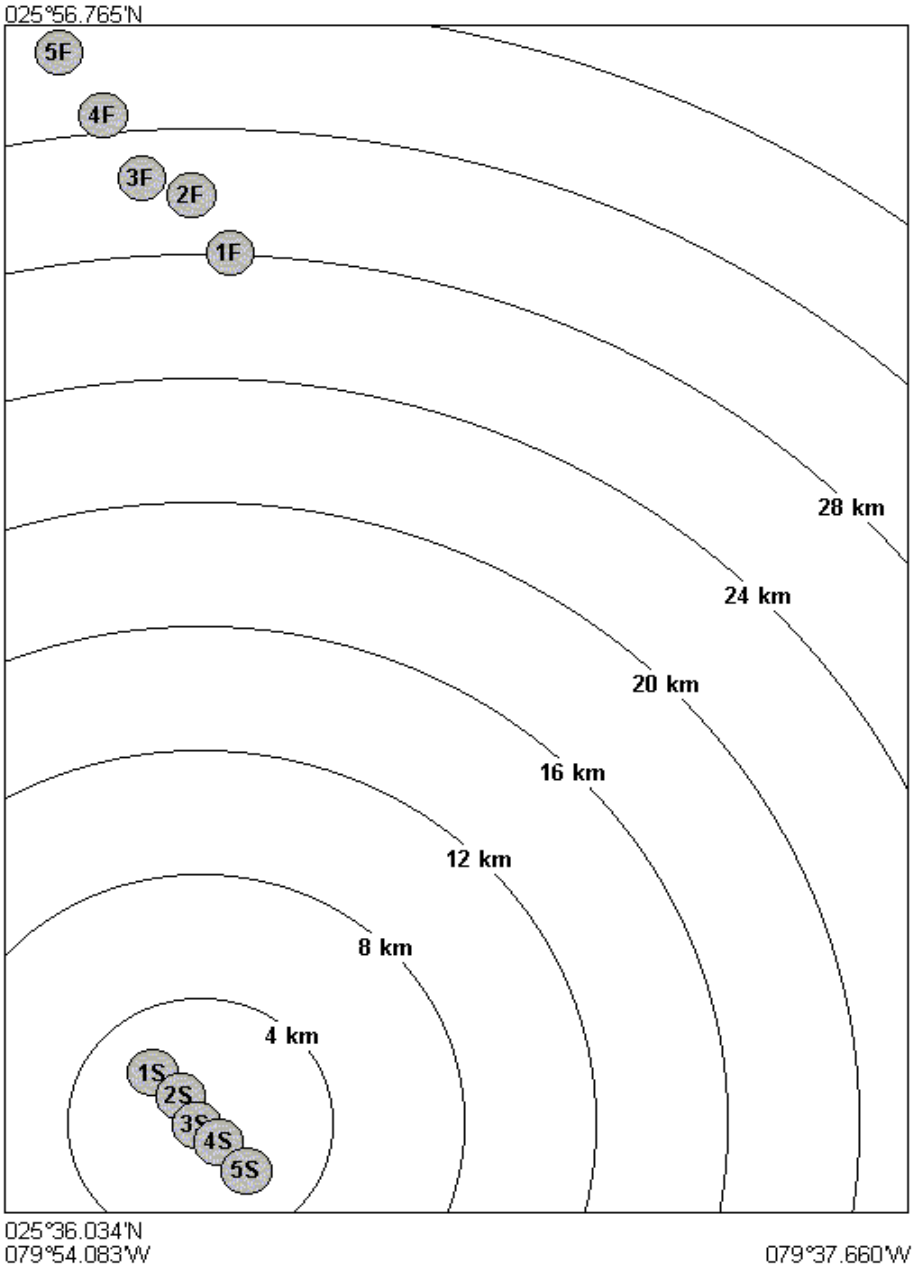


Figure A2. ***Paradise*** **Drifter Tracks (S-Start and F-Finish) for Set of Five Drifters Deployed and Recovered during the Miami Plume Tracking Survey.**

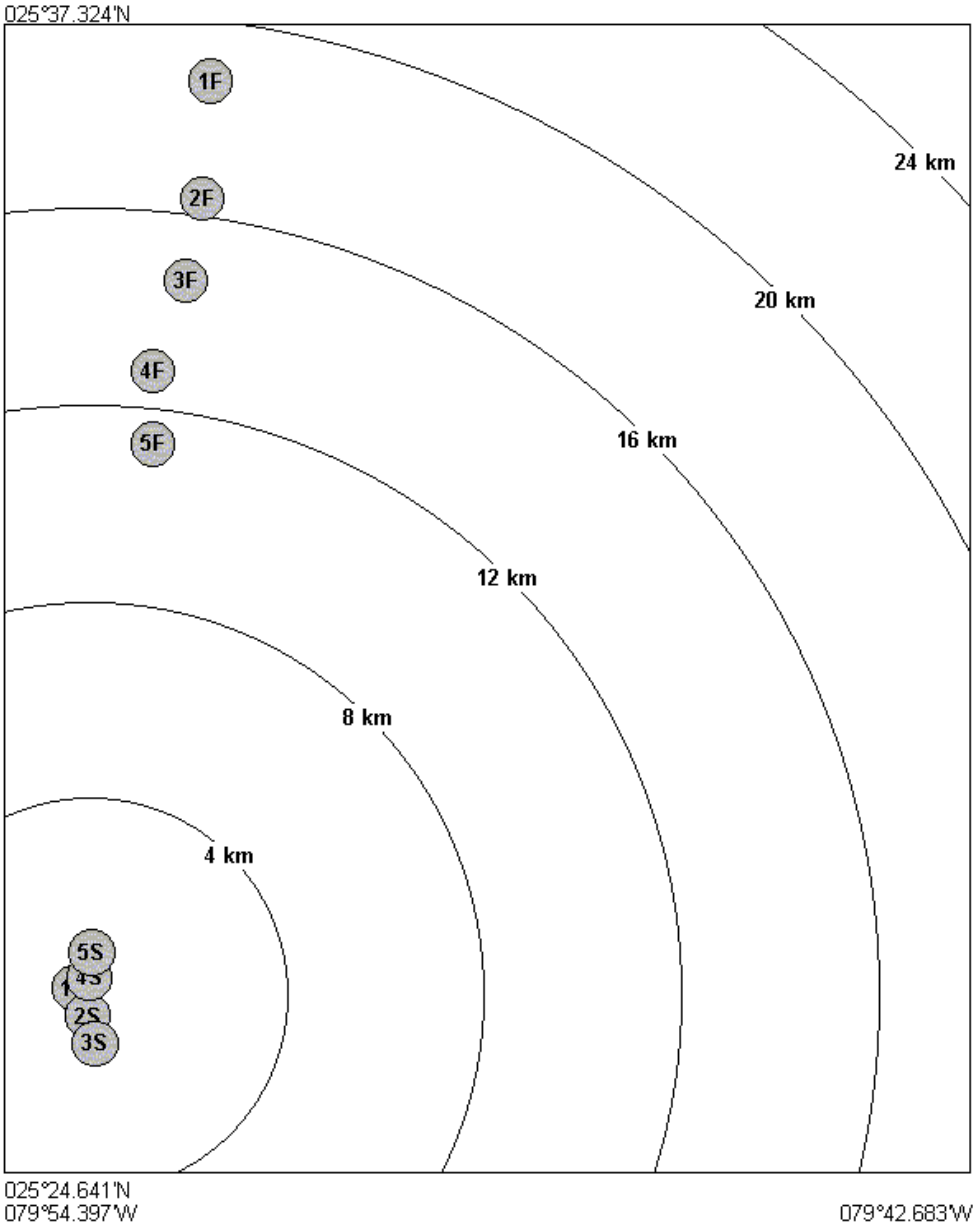


FIGURE A-3. ***FASCINATION*** **DRIFTER TRACKS (S-START AND F-FINISH) FOR SET OF FIVE DRIFTERS DEPLOYED AND RECOVERED DURING THE MIAMI PLUME TRACKING SURVEY.**

APPENDIX B

SAMPLING LOG TABLE

TABLE B-1. SURVEY SAMPLING LOG DATA (WA23PT).

Sample ID	Ship ID	Sample Type	Station ID	X position	Y position	Z position	Sample DateTime	Bathymetry	Comments
W23PT092	*Majesty*	Background	MA	-79.88248	25.92343	1.72	08/10/2001 16:nn:51	279.2	
W23PT095		Background	MA	-79.88265	25.92487	5.23	08/10/2001 16:nn:51	279.2	
W23PT099		Background	MA	-79.88290	25.92792	7.90	08/10/2001 16:nn:39	299.3	
W23PT09C		Background	MA	-79.88310	25.92938	4.79	08/10/2001 16:nn:25	298.3	
W23PT09F		Background	MA	-79.88323	25.93038	2.12	08/10/2001 16:nn:51	280.0	
W23PT0AD		Plume 1	MS	-79.88088	25.91123	1.77	08/10/2001 18:nn:52	291.3	
W23PT0B0		Plume 2	MM	-79.87875	25.91643	4.95	08/10/2001 18:nn:27	295.8	
W23PT0F9	*Explorer*	Background	EA	-79.87872	25.93027	2.15	08/11/2001 16:nn:28	301.8	
W23PT0FD		Background	EA	-79.87880	25.93005	4.79	08/11/2001 16:nn:29	117.7	
W23PT100		Background	EA	-79.87922	25.93278	8.16	08/11/2001 16:nn:43	140.0	
W23PT103		Background	EA	-79.87930	25.93365	9.99	08/11/2001 16:nn:18	140.5	
W23PT106		Background	EA	-79.87935	25.93422	12.03	08/11/2001 16:nn:18	128.9	
W23PT119		Plume 1	E1	-79.88685	25.91358	1.73	08/11/2001 19:nn:02	286.8	
W23PT11C		Plume 2	E1	-79.88557	25.91823	4.37	08/11/2001 19:nn:11	282.9	
W23PT11F		Plume 3	E1	-79.88425	25.92412	7.43	08/11/2001 19:nn:43	277.7	
W23PT122		Plume 4	E1	-79.88245	25.93236	2.50	08/11/2001 20:nn:44	300.3	hand entered
W23PT126		Plume 5	E2	-79.87970	25.94833	5.69	08/11/2001 20:nn:40	301.3	hand entered
W23PT16A	*Paradise*	Background	PA	-79.85248	25.63095	2.08	08/12/2001 18:nn:25	147.7	hand entered
W23PT171		Background	PA	-79.85277	25.63038	12.08	08/12/2001 18:nn:19	146.7	
W23PT174		Background	PA	-79.85278	25.63032	9.96	08/12/2001 18:nn:08	123.9	
W23PT177		Background	PA	-79.85280	25.63025	8.24	08/12/2001 18:nn:30	129.6	
W23PT17A		Background	PA	-79.85280	25.63022	4.91	08/12/2001 18:nn:01	148.4	
W23PT196		Plume 1	PD	-79.82998	25.62868	2.11	08/12/2001 19:nn:08	149.1	hand entered
W23PT199		Plume 2	PD	-79.82890	25.63082	8.45	08/12/2001 19:nn:02	127.6	hand entered
W23PT19C		Plume 3	PD	-79.82697	25.63947	10.31	08/12/2001 19:nn:16	144.9	hand entered
W23PT19F		Plume 4	PD	-79.82595	25.53440	12.68	08/12/2001 19:nn:39	123.5	hand entered
W23PT1A2		Plume 5	PD	-79.82447	25.65557	13.69	08/12/2001 19:nn:20	143.8	hand entered
W23PT1B2		Plume 6	P1	-79.81818	25.71717	5.00	08/12/2001 21:nn:34	148.5	
W23PT1BD		Plume 7	P1	-79.81831	25.75858	7.93	08/12/2001 21:nn:06	130.3	
W23PT1C0		Plume 8	P1	-79.81693	25.76465	7.93	08/12/2001 21:nn:09	129.4	
W23PT1E4	*Fascination*	Background	FA	-79.86463	25.49623	2.10	08/13/2001 18:nn:27	107.1	
W23PT1E7		Background	FA	-79.86465	25.49608	5.09	08/13/2001 18:nn:51	131.5	
W23PT1EA		Background	FA	-79.86470	25.49590	8.18	08/13/2001 18:nn:45	142.5	
W23PT1ED		Background	FA	-79.86477	25.49572	10.07	08/13/2001 18:nn:11	112.6	
W23PT1F0		Background	FA	-79.86487	25.49542	12.44	08/13/2001 18:nn:04	92.3	
W23PT203		Plume 1	FD	-79.89098	25.44878	2.48	08/13/2001 19:nn:29	101.0	
W23PT206		Plume 2	FD	-79.89038	25.45128	4.75	08/13/2001 19:nn:52	89.8	hand entered
W23PT20A		Plume 3	FD	-79.88975	25.45665	8.08	08/13/2001 19:nn:08	140.3	
W23PT20D		Plume 4	FD	-79.88860	25.46193	12.04	08/13/2001 19:nn:33	85.2	
W23PT210		Plume 5	FD	-79.88792	25.46668	15.20	08/13/2001 20:nn:49	146.9	
W23PT215		Plume 6	F1	-79.88635	25.48020	2.64	08/13/2001 20:nn:20	148.1	hand entered
W23PT219		Plume 7	F1	-79.88723	25.48180	2.41	08/13/2001 20:nn:07	118.8	hand entered
W23PT21B		Plume 8	F1	-79.88603	25.48833	8.12	08/13/2001 20:nn:02	86.1	
W23PT21E		Plume 9	F1	-79.88564	25.48873	8.18	08/13/2001 20:nn:42	137.2	

APPENDIX C

SHIP TRACKS SHOWING DYE 2 CONCENTRATIONS VS. DEPTH USING COLOR CODES

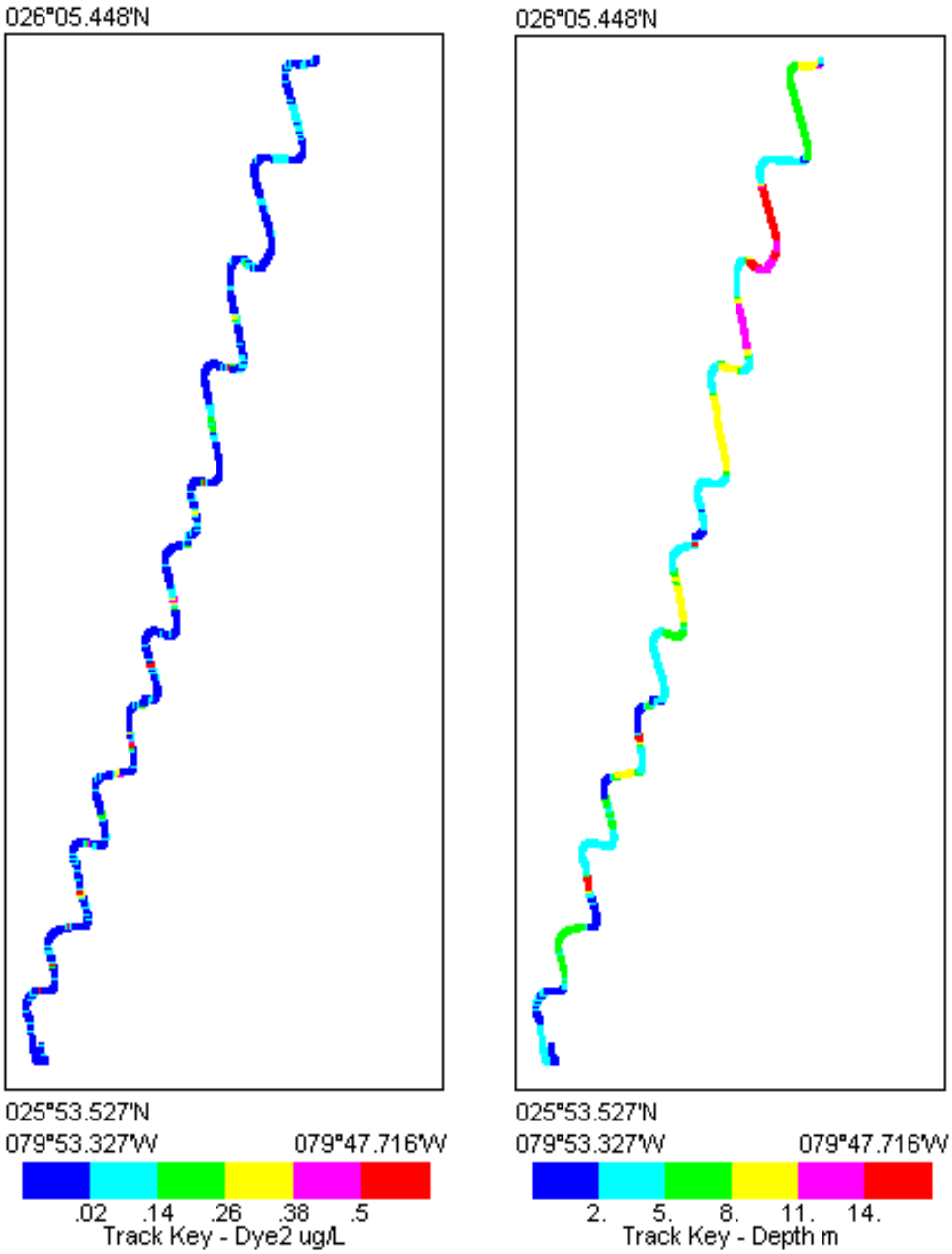


Figure C-1 ***Majesty*** **Track – Dye/Depth**

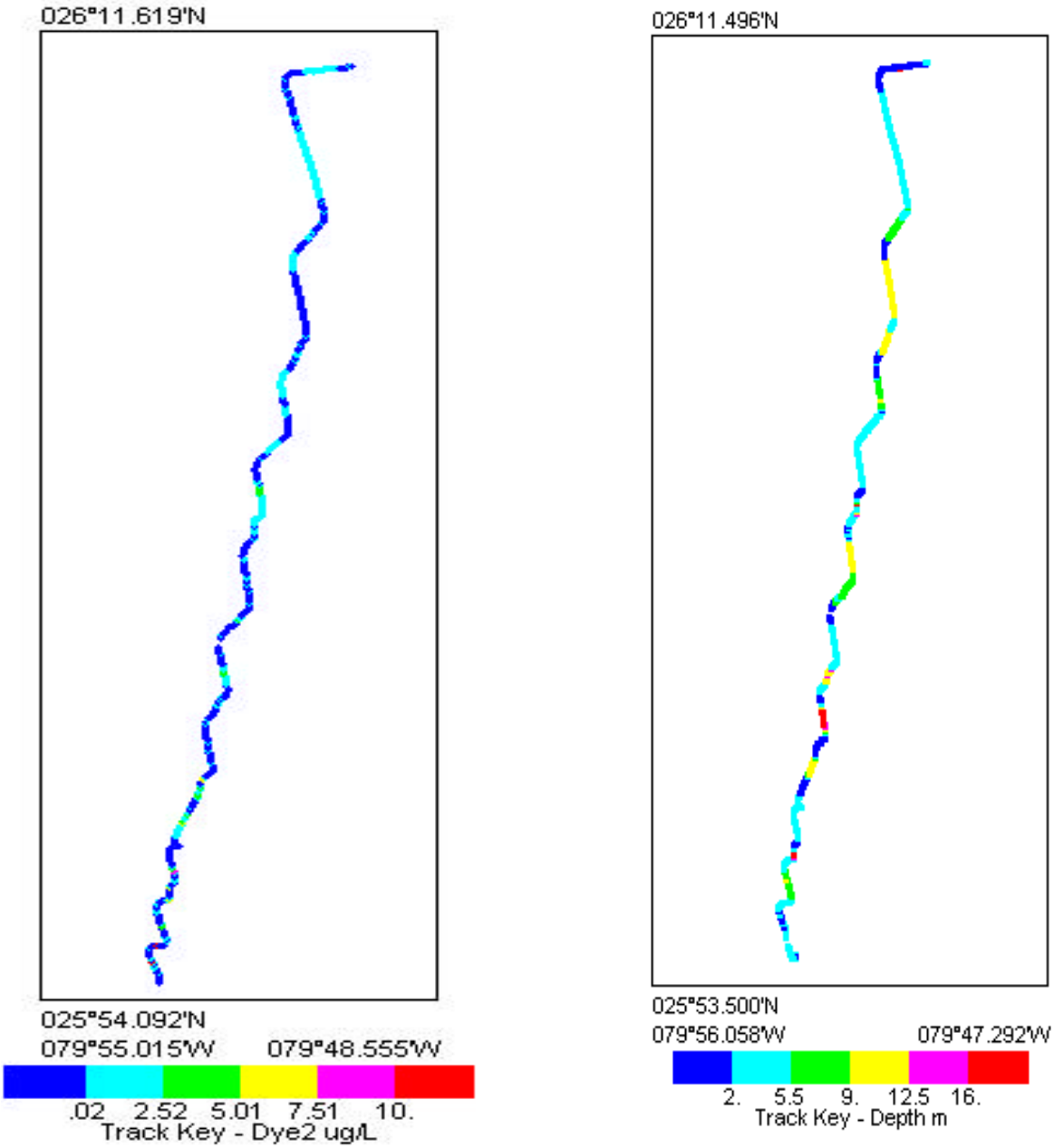


Figure C-2. *Explorer* Track - Dye/Depth

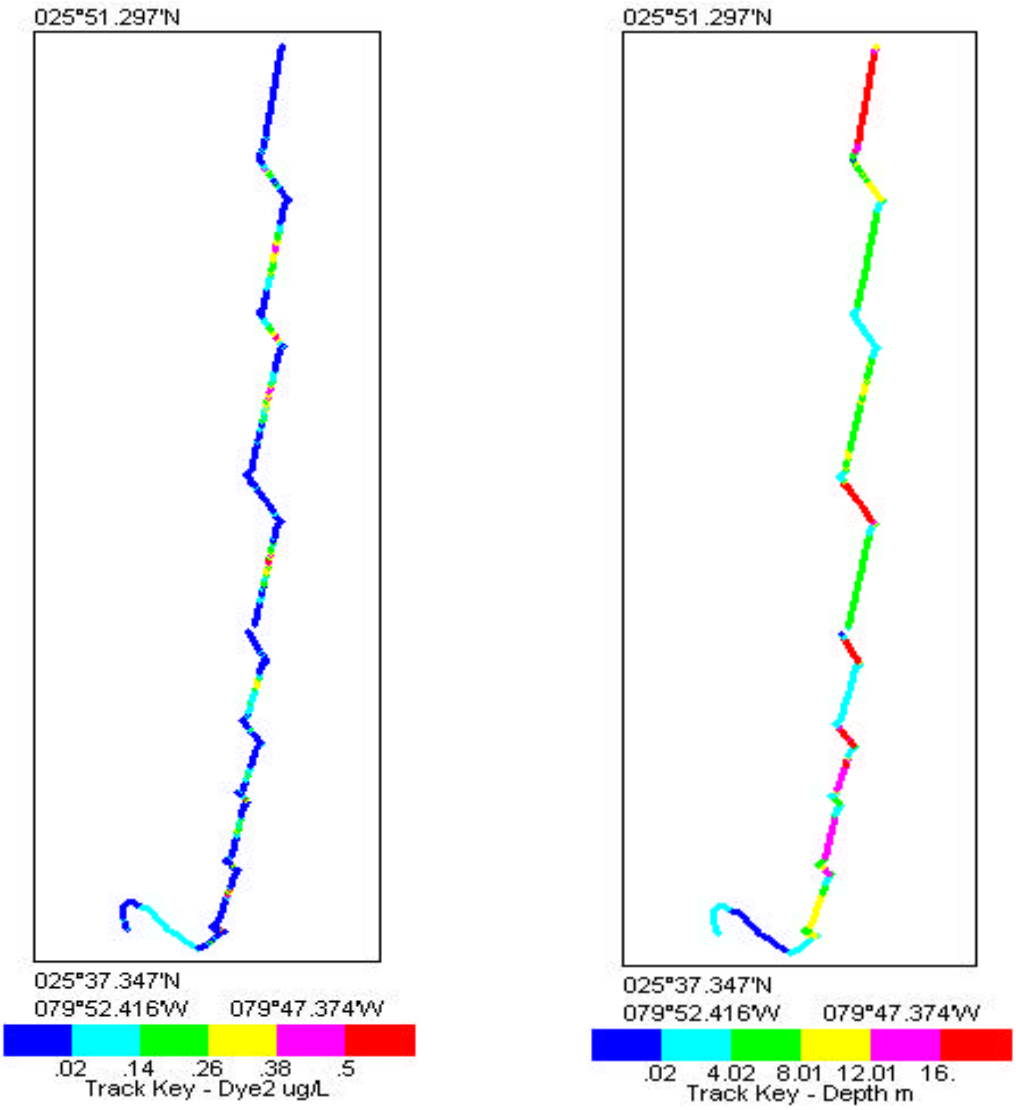


Figure C-3. *Paradise* Track – Dye/Depth.

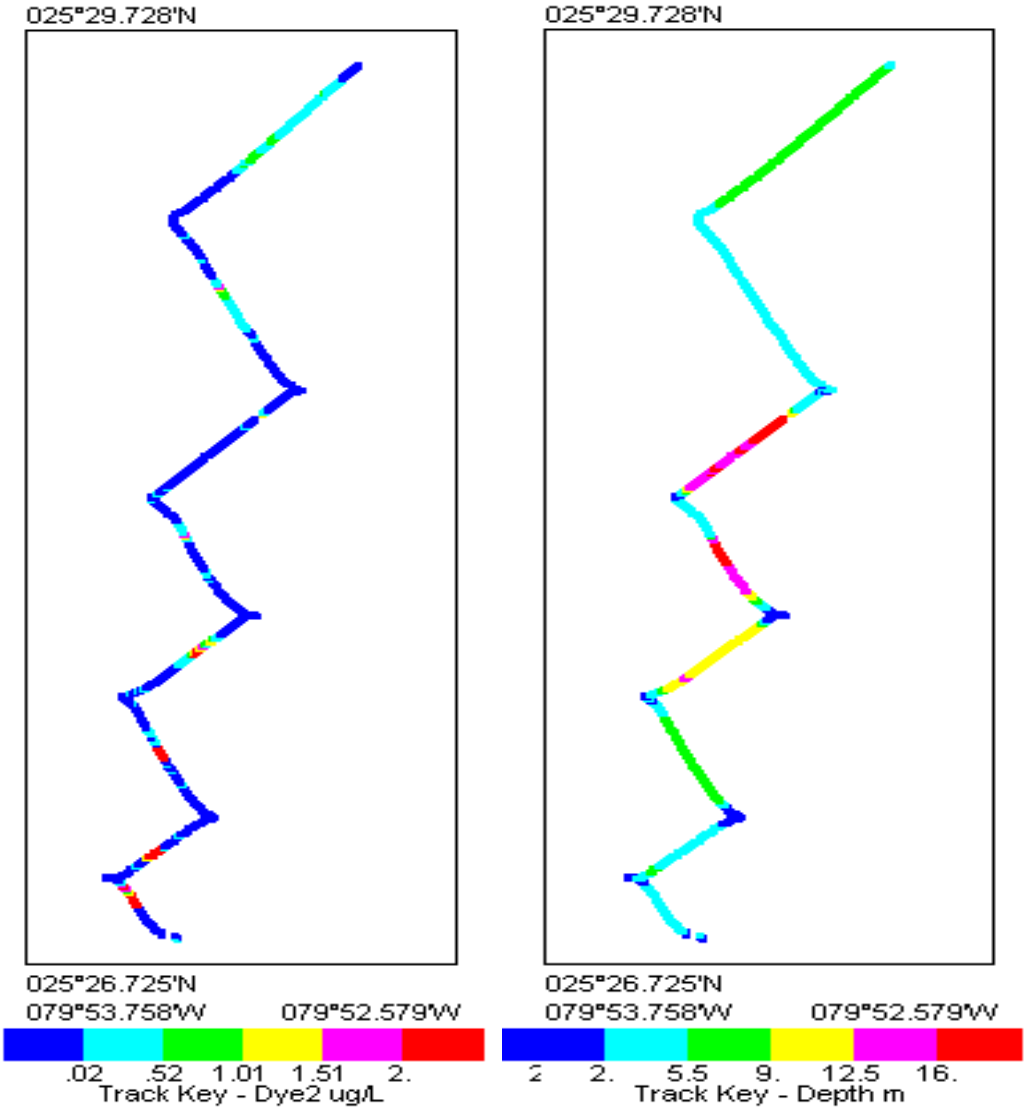


Figure C-4. ***Fascination*** **Track - Dye/Depth**

APPENDIX D

TIME SERIES PLOTS OF DEPTH VS. DYE FOR EACH CRUISE SHIP/PLUME TRACKED

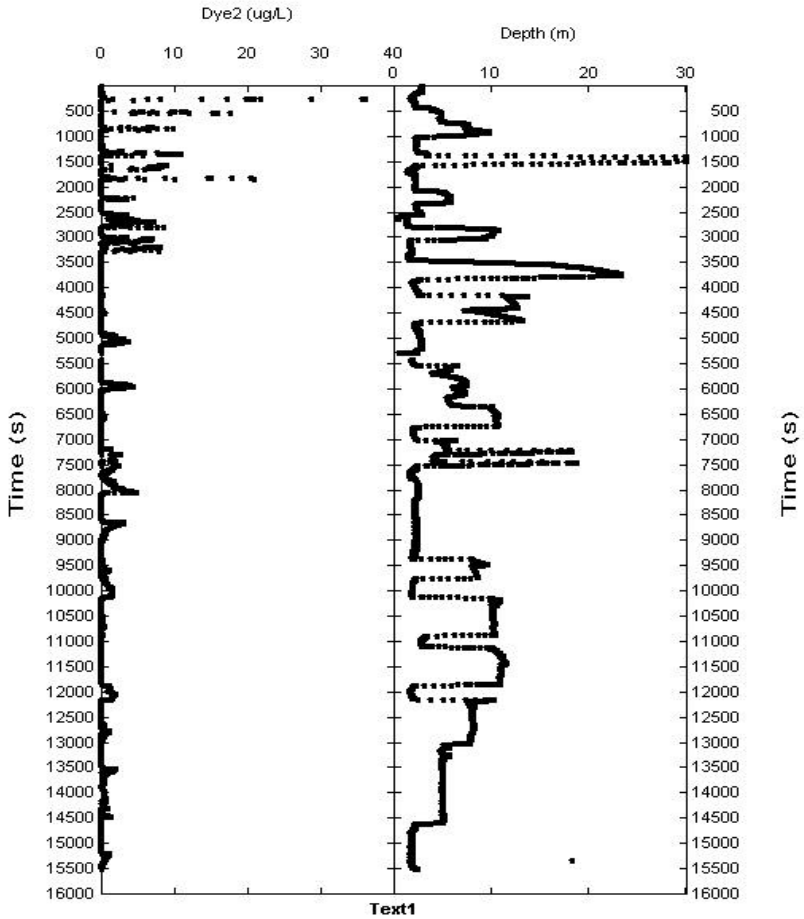


Figure D -1. Majesty Time Series Plot of Dye Concentration vs. Depth for All Transect Passes Through Plume.

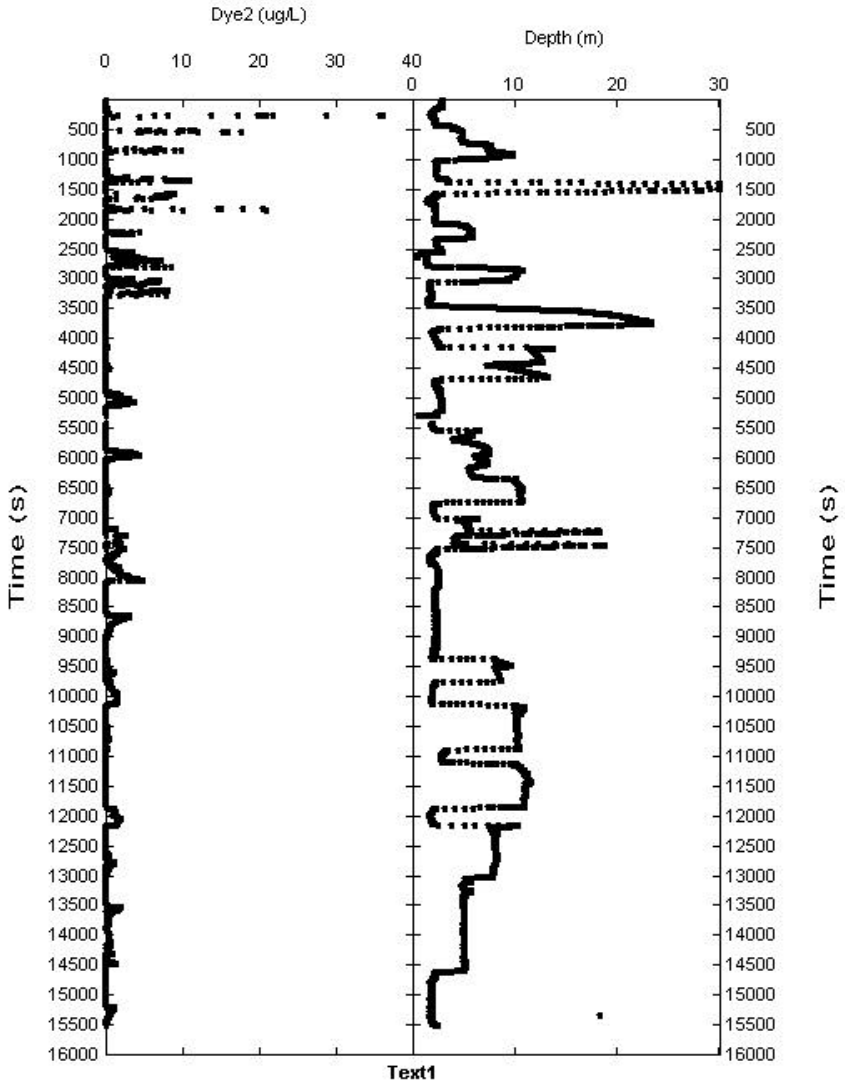


Figure D-2. .Explorer Time Series Plot of Dye Concentration/Depth for All Transect Passes Through the Plume.

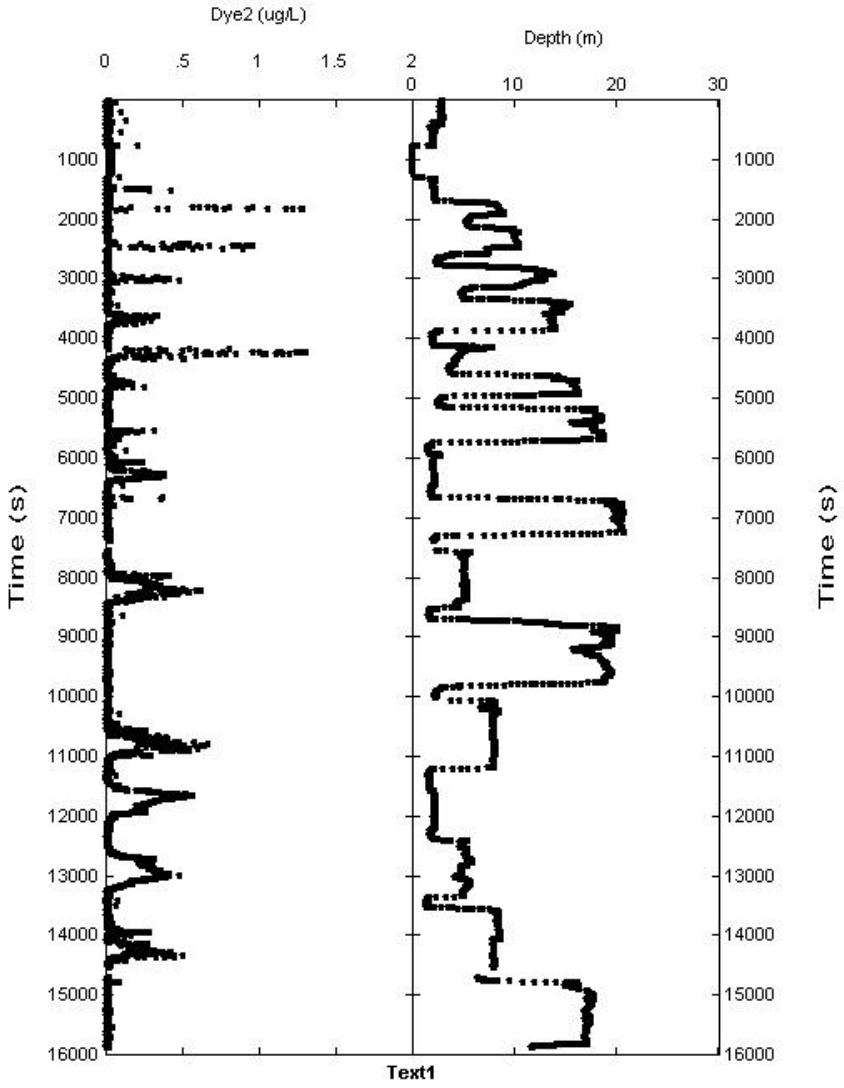


Figure D-3. Paradise Dye Concentration/Depth for All Transect Passes Through the Plume.

APPENDIX E

SCATTER PLOTS OF DYE 2 CONCENTRATION VS. DEPTH

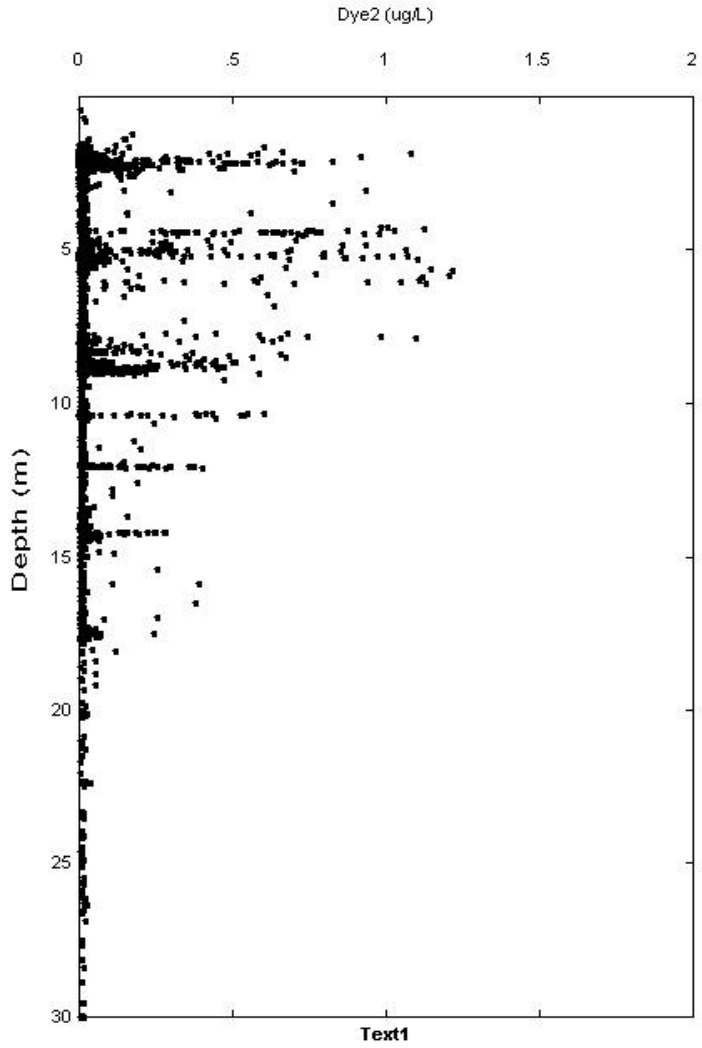


Figure E -1. Scatter Plot of Dye Concentration/Depth for Majesty.

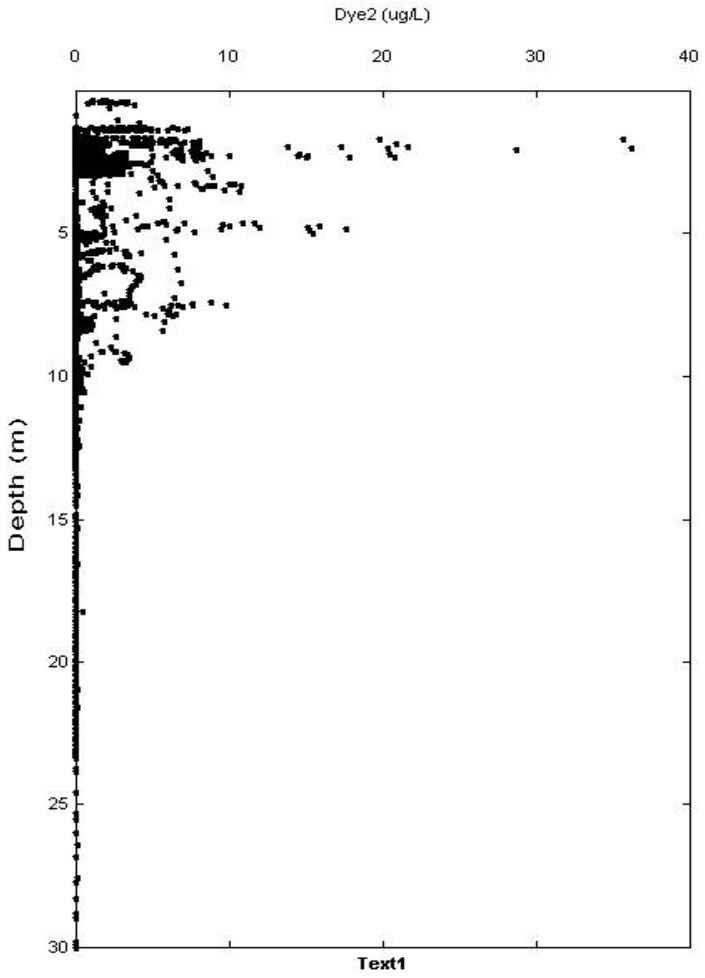


Figure E-2. Scatter Plot of Dye Concentration/Depth for Explorer.

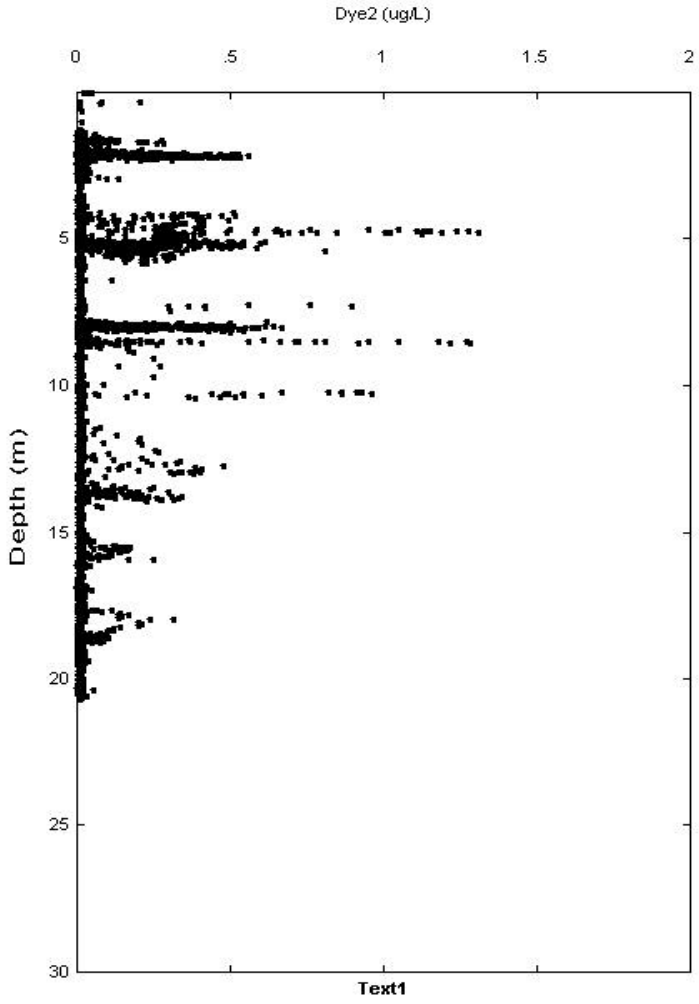


Figure E-3. Scatter Plot of Dye Concentration/Depth for Paradise.

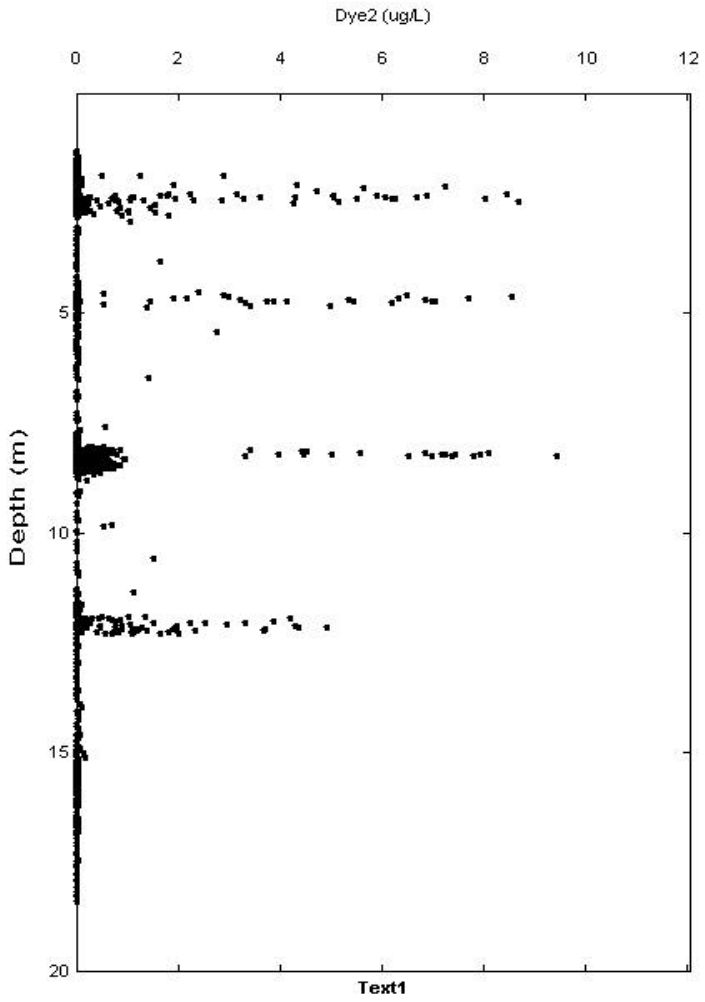


Figure E -4. Scatter Plot of Dye Concentration/Depth for Fascination.

APPENDIX F

DISCRETE DYE SAMPLE DATA

Table F-1. Discrete Dye Sample Data Collected from Each Plume Used for Calibrating the *in-situ* Rhodamine Dye Sensor

Ship	Sample ID	Dye Concentration (ug/l)
Majesty	W23PT092	MDL
	W23PT095	MDL
	W23PT099	MDL
	W23PT09C	MDL
	W23PT09F	MDL
	W23PT0AD	0.446
	W23PT0B0	0.532
Explorer	W23PT0F9	MDL
	W23PT0FD	MDL
	W23PT100	MDL
	W23PT103	MDL
	W23PT106	MDL
	W23PT119	25.658
	W23PT11C	0.563
	W23PT11F	4.529
	W23PT122	2.002
	W23PT126	0.207
Paradise	W23PT16A	MDL
	W23PT171	MDL
	W23PT174	MDL
	W23PT177	MDL
	W23PT17A	MDL
	W23PT196	MDL
	W23PT199	0.426
	W23PT19C	0.527
	W23PT19F	0.075
	W23PT1A2	MDL
	W23PT1B2	0.116
	W23PT1BD	MDL
	W23PT1C0	0.129
Fascination	W23PT1E4	0.433
	W23PT1E7	MDL
	W23PT1EA	MDL
	W23PT1ED	MDL
	W23PT1F0	MDL
	W23PT203	3.629
	W23PT206	1.166
	W23PT20A	2.707
	W23PT20D	MDL
	W23PT210	MDL
	W23PT21B	0.365
	W23PT21E	0.439
	W23PT215	MDL
	W23PT219	1.280

Table F-2. Measured Dye Concentrations and Average Concentration for Each Cruise Ship Monitored during the Survey.

Ship	Sample ID	Value ug/L	Tank Conc. (ug/L) (after accounting for dilution)	Tank Conc. (g/L)	Average Tank Conc. (g/L)	Calculated Tank Conc. (g/L)	Amount of Dye Added (gallons)	Amount of Dye Added (kg)
Explorer	ET=1D	0.54	1077030.44	1.08	1.00	1.44	35	26.4kg
	ET=2C	41.90	838024.33	0.84				
	ET=3C	42.79	855741.66	0.86				
	ET=4C	23.29	465898.95	0.47				
	ET=OD	0.89	1773055.80	1.77				
			Sum	5.01				
Fascination	FT=1D	2.45	980549.92	0.98	0.98	1.00	36	27.1kg
	FT=2D	1.54	615647.82	0.62				
	FT=3D	1.29	517182.18	0.52				
	FT=4D	1.00	401364.81	0.40				
	FT=OD	5.97	2388029.43	2.39				
			Sum	4.90				
Majesty	MT=0	<0.024		0.00	0.14	0.20	30	22.6kg
	MT=1C	10.19	101881.14	0.10				
	MT=2C	12.37	123746.47	0.12				
	MT=3C	14.17	141709.15	0.14				
	MT=4C	17.32	173159.56	0.17				
			Sum	0.54				
Paradise	PT=1C	17.30	173018.30	0.17	0.27	0.24	35	26.4kg
	PT=2C	18.42	184170.35	0.18				
	PT=3C	34.23	342336.78	0.34				
	PT=4C	42.55	425474.73	0.43				
	PT=OC	22.72	227152.75	0.23				
			Sum	1.35				

*Not used in calculations

APPENDIX G

CALCULATIONS FOR CALCULATED VS. MEASURED DYE DILUTIONS FOR EACH CRUISE SHIP.

M/S Majesty

Majesty calculated dye concentration in tank

Volume of graywater in tank (V_{gw}) - 113 m^3 X 1000L/m^3 =113,000L graywater/blackwater
Volume of dye (V_{dy}) - 30gal . dye = 113.6L
Vgw + Vdy = 113,114
Wt. Of active ingredient in 30 gal, dye - 22.6 kg active ingredient/114 L dye
therefore Concentration of active ingredient in tank **(C_{tc})** = 22.6kg dy/113,114 L gw or 22600 g dy/113,114 L gw

Calculated Tank Dye Concentration (C_{tc})= 0.1998 g dy/L

Measured Tank Dye Concentration (C_{tm}) from Appendix F -Table F- 2 = 0.13512 g dy/L

Amount of dye not discharged (left in the tank)

Of the 113,114 L of Dye in the tank at the initiation of pumping 7000 L (7 m^3) were not pumped overboard.
0.1998 g dy/L (conc dye in tank)= Xg/7000L where X=amount of dye not discharged
0.1998 g dy/L* 7000 L = X_g = **1398.6 g dy**

Distance traveled D_x in 57 min at a speed of 17.4 kts.

D_X/57=17.4/60
Dx = 57 min. * 17.4 kts./60 min.
Dx = 991.8 min kts./60 min
Dx = 16.5 nmi traveled

Majesty calculated initial concentration based on length (ship pumping specifications - Table 2), width, and depth of initial plume transect.

Plume dimensions and volume

1 nmi = 1852 m
1852 x 16.5 = 30,558 m
Plume width = width of plume at first transect = 66m
Depth of plume ~ 18 m
Volume of plume~ 66m * 18m * 30,558= 36,302,904 m^3 * 1000L/m^3 = 36,302,904,000 L

Calculated concentration of dye in plume (C_{pc}) = g/L

C_{pc} = 22600g – X_g from above/36,302,904,000 = 22600g –1399g/36,302,904,000 L= 21201/36,302,904,000 L
C_{pc} = 5.84 * 10(-7) g/L =

***Majesty* Initial Calculated Dye Concentration (C_{pc}) = 0.584 ug/L**

***Majesty* - Calculated Dilution = Tank Concentration/Seawater Concentration**

0.1998g/0.584ug/L = 0.1998g/L/.000000584g/L =

***Majesty* Calculated Dilution = 342,123:1**

***Majesty* - Average Initial Measured Dye Concentration (dye 2) in Plume = 0.35 µg/L (First Transect)**

***Majesty* - Measured Dilution = Tank Concentration/Seawater Concentration**

0.13512g/L/0.35ug/L = 0.13512g/L/.00000035g/L =

***Majesty* Measured Dilution 386,057:1**

M/S Explorer

Explorer calculated dye concentration in tank

Volume of blackwater and dye in tank (V_{bw+dy}) - 18.3 m^3 *1000L/m^3 =18,300L gw+dye
Volume of dye (V_{dy}) - 35 gal. dye = 133 L (already measured as part of the gray water volume)
Wt. Of active ingredient in 35 gal (133 L) dye - 26.4 kg active ingredient/133 L dye
26.4kg dy/18300 L gw+dye therefore 26400 g dy/18300 L gw+dye

Calculated Tank Dye Concentration =1.443 g/L
Measured Tank Dye Concentration = 1.002 g/L

Amount of dye not discharged (left in the tank)

Of the 18300 L of Dye in the tank at the initiation of pumping 1200 L (1.2 m^3) were not pumped overboard.
1.443 g dy/L (conc dye in tank)= Xg/1200 L where X=amount of dye not discharged
1.443 g dy/L* 1200 L = X_g = **1731 g dy**

Distance traveled (D_X) in 18 min at a speed of 19 kts.

D_X /18=19/60
D_X =18 min.*19 kts./60 min.
D_X = 342 minkts./60 min
D_X = 5.7 nmi traveled

Explorer calculated initial concentration based on length (ship pumping specifications - Table 2), width, and depth of initial plume transect.

Plume dimensions and volume

1 nmi = 1852 m
1852 x 5.7 nmi =10556
Plume width = width of plume at first transect = 147m
Depth of plume ~ 10 m
Volume of plume~ 147m * 10m * 10556 = 15,517,320 m^3 * 1000L/ m^3 = 15,517,320,000 L

Calculated concentration of dye in plume (C_{pc}) = g/L

C_{pc} = 26400g – X_g dy from above/15,517,320,000L = 26400g –1731g dy/15,517,320,000L= 24,669g dy/15,517,320,000L
1.59 * 10(-6)g/L =

***Explorer* - Calculated Initial Dye Concentration = 1.59 ug/L**

***Explorer*- Calculated Dilution = Tank Concentration/Seawater Concentration**
1.443g/L/1.59ug/L =1.443g/L.00000159g/L =
***Explorer* Calculated Dilution = 907,547:1**

***Explorer* - Average Initial Measured Dye Concentration (Dye 2) in Plume = 5.13 ug/L (First Transect)**
***Explorer* - Measured Dilution = Tank Concentration/Seawater Concentration**
1.002g/5.13ug/L = 1.002g/.00000513g/L =
***Explorer* Measured Dilution = 195,321:1**

M/S Paradise

Paradise calculated dye concentration in tank

Volume of graywater in tank (V_{gw}) - 108 m^3 * 1000L/ m^3 = 108,000L gw+dye
Volume of dye (V_{dy}) 35gal . = 133 L dye
Vgw + Vdy = 108,133
Wt. Of active ingredient in 35 gal (133 L) dye - 26.4 kg active ingredient/133 L dye
26.4 kg dye/108,133L gw+dy therefore 26400 g dy/108,133 L gw+dy

Calculated Tank Dye Concentration = 0.244 g/L
Measured Tank Dye Concentration = 0.2704 (from Table F-2 in Appendix F)

Amount of dye not discharged (left in the tank)

Of the 108,133 L (108.133 m^3)of dye + graywater in the tank at initiation of pumping 40,000 L (40 m^3) were not pumped overboard (pumping lasted for 30 min).
0.244 g/L (conc dye in tank) = Xg/40,000L where Xg = amount of dye not discharged
0.244 g/L * 40,000L =Xg therefore Xg = 9765g

Distance traveled (D_X) in 30 min at a speed of 15 kts.

D_X /30=15/60
D_X =30 min * 15 kts./60 min.
D_X = 450 min kts./60 min
D_X = 7.5 nmi traveled

Paradise calculated initial plume concentration based on length (ship pumping specifications - Table 2), width, and depth of initial plume transect.

Plume dimensions and volume

1 nmi = 1852 m/nmi
1852 * 7.5=13,890 m
Plume width = width of plume at first transect = 182 m
Depth of plume ~ 18 m
Volume of plume~ 182m * 18m * 13890= 45,503,640 m^3 * 1000L/m^3 = 45,503,640,000 L

Calculated concentration of dye in plume (C_{pc}) = g/L

26400 g - Xg from above/45,503,640,000 L = 26400g –9765g/45,503,640,000 L =
16635/45,503,640,000 L = 3.656 *10(-7) g/L =

***Paradise* Initial Calculated Dye Concentration = 0.3656 ug/L**

***Paradise* Calculated Dilution = Tank Concentration/Seawater Concentration**
0.244g/L/0.366ug/L = 0.244g/L/.000000366g/L =

***Paradise* Calculated Dilution =666,667:1**

***Paradise* - Average Initial Measured Dye Concentration (Dye 2) in Plume = 0.42 ug/L (First Transect)**

***Paradise* - Measured Dilution = Tank Concentration/Seawater Concentration**
0.2704g/L/0.42ug/L = 0.2704g/L/.00000042g/L =

***Paradise* Measured Dilution = 643,809:1**

M/S Fascination

Fascination calculated concentration in tank

Volume of graywater in tank (V_{gw}) - 27m^3 * 1000L/m^3 =27,000L gw
Volume of dye (V_{dy}) 36gal . = 137 L dye
Vgw + Vdy = 27,137
Wt. Of active dye ingredient in 36 gal, 27.1 kg dye
27.1 kg dye/27,137L gw+dy therefore 27100 g dy/27,137 L gw+dy

Calculated Tank Dye Concentration = 0.999 g/L
Measured Tank Dye Concentration = 0.9806 (from Table F-2 in Appendix F)

Amount of dye not discharged (left in the tank)

Of the 27,137 L (108.1370m^3) of Dye in the tank at initiation of pumping
3000 L (3 m^3) were not pumped overboard. (pumping lasted for 30 min).
0.999 g/L (conc dye in tank)= Xg/3,000L where Xg=amount of dye not discharged
0.999g/L * 3,000L = Xg therefore Xg = 2997g

Distance traveled in 20 min at a speed of 9.1 kts.

X/20=9.1/60
X =20 min * 9.1 kts./60 min.
X= 182 min kts./60 min
X = 3.03 nmi traveled

FASCINATION CALCULATED INITIAL CONCENTRATION BASED ON LENGTH (SHIP PUMPING SPECIFICATIONS - TABLE 2), WIDTH, AND DEPTH OF INITIAL PLUME TRANSECT.

Plume Dimensions and Volume

1852 * 3.03=5612 m
Plume width = width of plume at first transect = 88m
Depth of plume ~ 12.5 m
Volume of plume~ 88m x 12.5m x 5612= 6,172,100 m^3 * 1000L/m^3 = 6,172,100,000 L

Calculated concentration of dye in plume (C_{pc}) = g/L

27100 g - Xg from above/6,172,100,000 L = 27100g dye –2997g/6,172,100,000 L =
24103g dye/6,172,100,000 L = 3.91 * 10(-6) g/L =

Initial Calculated Dye Concentration = 3.91 ug/L

***Fascination* - Calculated Dilution = Tank Concentration/Seawater Concentration**
0.999g/3.91ug = 0.999g/.00000391g/L =

***Fascination* Calculated Dilution = 255,499:1**

***Fascination* -Average Measured Dye Concentration (Dye 2) in Plume= 3.4 ug/L (First Transect)**
Fascination Measured Dilution = Tank Concentration/Seawater Concentration
0.9806g/L/3.4ug/L = 0.9806g/L/.0000034g/L =

***Fascination* Measured Dilution = 288,411:1**