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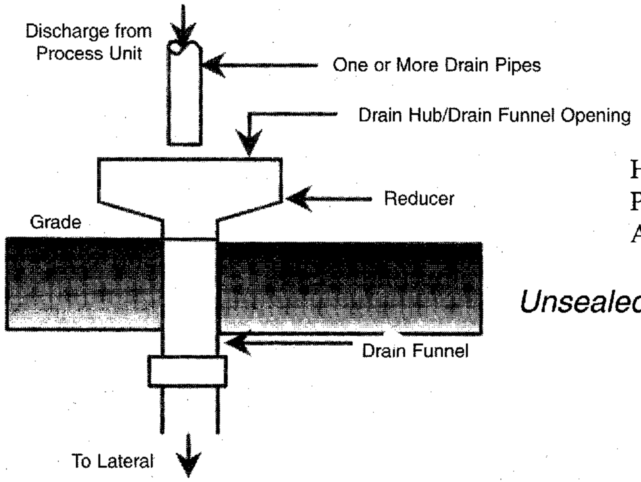
STEP Strategies for Today's Environmental Partnership

FUGITIVE EMISSIONS FROM REFINERY PROCESS DRAINS VOLUME I

FUGITIVE EMISSION FACTORS FOR REFINERY PROCESS DRAINS



Unsealed Drain

HEALTH AND ENVIRONMENTAL SCIENCES DEPARTMENT
PUBLICATION NUMBER 4677
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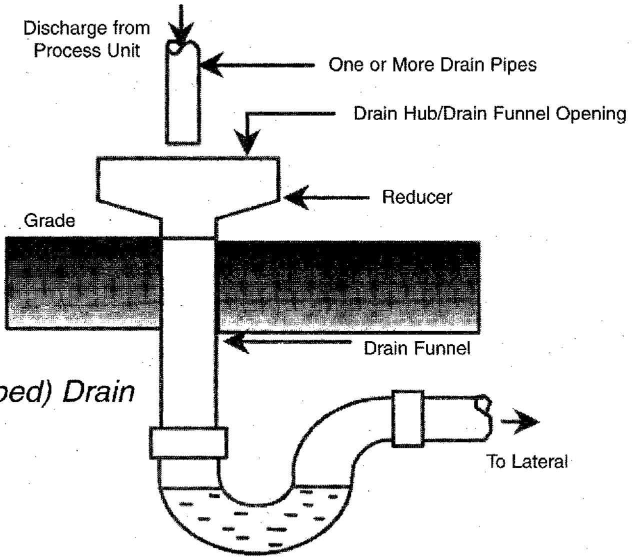

Sealed (Trapped) Drain

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- To participate with government and others in creating responsible laws, regulations and standards to safeguard the community, workplace and environment.
- To promote these principles and practices by sharing experiences and offering assistance to others who produce, handle, use, transport or dispose of similar raw materials, petroleum products and wastes.

Fugitive Emissions From Refinery Process Drains
Volume I

Fugitive Emission Factors For Refinery Process Drains

Health and Environmental Sciences Department

API PUBLICATION NUMBER 4677

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PREFACE

The results of this study are presented in three separate reports.

- Volume I entitled "*Fugitive Emission Factors for Refinery Process Drains*" (API Publication Number 4677) contains simplified emission factors that can be used to quickly estimate total volatile organic compound (VOC) emissions from refinery process drains.
- Volume II entitled "*Fundamentals of Fugitive Emissions from Refinery Process Drains*" (API Publication Number 4678) describes theoretical concepts and equations that may be used in a model (APIDRAIN) to estimate speciated VOC emissions. The model can provide insight on how to change process drain variables (flow rate, temperature, etc.) to reduce emissions.
- Volume III entitled "*APIDRAIN Version 1.0, Process Drain Emission Calculator*" (API Publication Number 4681) is the computer model with user's guide to estimate emissions from refinery process drains. The software allows users to calculate VOC emissions based on the emission factors in Volume I and equations for speciated emissions in Volume II.

All three volumes of this study can be purchased separately; however, it is suggested that the user consider purchase of the entire set to gain a complete understanding of fugitive emissions from refinery process drains.

ABSTRACT

Fugitive emissions are estimated using USEPA's emission factors from the publication known as AP-42. The factor for refinery process drains was first developed in 1979. Drain modifications and sewer system improvements have reduced emissions, with the result that the AP-42 emission factor may overestimate drain emissions. The refinery process drain emission factor has also been applied to non-process drains, with the result that drain emissions are now a significant component of refinery emissions. This work was undertaken to address these concerns. Laboratory- and pilot-scale drain systems were constructed and tests were conducted to develop emission factors and to evaluate the mechanics of emissions from active, trapped process drains. A model was developed to estimate emissions from process drains.

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EXECUTIVE SUMMARY

This investigation was initiated by the American Petroleum Institute (API) to update the AP-42 emission factor for refinery process drains, which may overestimate refinery process drain fugitive emissions. Changes in refinery process drains have been implemented in response to United States Environmental Protection Agency (USEPA) regulations, including benzene waste operations National Emission Standards for Hazardous Air Pollutants (NESHAP) and New Source Performance Standards (NSPS) Subpart QQQ. Sealed drains have led to lower refinery process drain emission conditions, compared with conditions when the AP-42 emission factor was developed. The results of this study indicate that the AP-42 emission factor for refinery process drains should be modified.

The work reported in this report is the second phase of an effort to develop new emission factors to improve the estimate of drain emissions. This report presents new emission factors based on the flow and loadings into laboratory- and pilot-scale process drains. The emission factors require a knowledge of the concentrations of various constituents in the process wastewater discharged to the refinery drains. Specific project activities are summarized below.

Protocols for field bagging and measuring drain emissions were tested. Results indicated that vacuum and blow-through bagging protocols give the same results. For the least volatile constituents, emissions were statistically greater for a drain with no bag than for a drain enclosed by a bag.

A series of emission factor tables were developed, which are more appropriate for estimating drain emissions than using a single emission factor. The emission factor tables require a knowledge of the volatility of the constituents discharged to the drain, the physical parameters of the drain, and the amount of time (hours per day) the drain is used. The emission factor tables were developed using the wastewater mass balance method, because it was shown to be more accurate than the gas sampling method during the pilot-scale studies. Experiments for the emission factor tables used the misaligned hub configuration to conservatively promote emissions.

A model was developed to describe drain emission mechanics. The model includes estimates of air entrainment, degree of chemical equilibrium, and gas- and liquid-phase mass transfer coefficients associated with volatilization across the surface of a water seal. The existing

USEPA model, WATER8, may significantly overestimate stripping efficiencies from process drains that contain water seals. The reader has the option of using either the model or the emission factor tables.

Field studies to test drain emissions were difficult to implement because of the impact of benzene waste operations NESHAP. Tests were conducted at one refinery, but the emissions were too low for any meaningful conclusions.

1. INTRODUCTION

This project develops a set of emission factor tables that can be used to replace the AP-42 emission factor for refinery process drains. The project also develops a two-phase model to predict the emissions from refinery process drains, and this model can also be used to replace the emission factors from AP-42. The AP-42 factor is only viable for process drains and for drains without a water seal. Many refinery drains have been retrofitted with a seal to reduce these emissions. New emission factors or approaches to develop new emission estimates are thereby warranted.

The project was completed in a number of tasks. Their significant activities and findings are presented below.

PILOT-SCALE VERIFICATION OF DRAIN BAGGING PROTOCOL

The results are presented in Chapter 2 of this report. The most significant finding was that emissions for five of the six compounds tested are statistically greater from a bagged drain than from a drain with no bag. The five compounds were all of the less volatile compounds.

PILOT-SCALE DETERMINATION OF STRIPPING EFFICIENCIES

The results are presented in Chapter 3 of this report. The stripping efficiency tests resulted in a series of emission tables that can be used instead of the AP-42 emission factor when wastewater composition and flow rate characteristics are known. These emission factor tables yield much lower emissions than the AP-42 emission factor when using realistic conditions of refinery drain activity.

MODEL PARAMETER ESTIMATION AND ANALYSIS OF EFFECTS OF AMBIENT CONDITIONS ON EMISSIONS

The results are presented in API Publication Number 4678. A two-zone model was developed for estimating volatile organic compound (VOC) emissions from refinery process drains. One zone was above the water seal and one zone was below. The laboratory investigations developed factors based on fundamental mass transfer kinetics and allow for a range of operating conditions and environmental factors. A significant finding is that the existing EPA model may significantly overestimate emissions from refinery process drains that contain water seals. These results are presented in API Publication Number 4678.

FIELD DRAIN EMISSION MEASUREMENTS

This effort was begun but the field measurements were conducted at a refinery that had collected all its wastewater and sealed its drains in compliance with benzene waste operations NESHAP. Thus, there were no process drains that met even minimal levels (100 ppm VOCs) of emissions that could be used to test the bagging protocols, the emission factor tables, or the model. Thus, these tests were discontinued.

This effort highlighted the changes that refinery process drains have undergone in the 1990s. When the drains were first being included in emission inventories, the emission factor for refinery process drains was the only emission factor available. Thus, this emission factor was used for storm sewers, non-process sewers, indeed virtually any drain of any sewer in a refinery. This report presents an improved emission factor that more accurately reflects emissions from sealed, process drains in a petroleum refinery.

2. Pilot Scale Determination of Drain Bagging Protocol

The objective was to experimentally determine the impact of gas sampling procedures (that is, bagging) on emission rates from an active, aligned process drain sealed with a P-trap. Percentage emissions and mass emission rates were calculated using wastewater contaminant concentrations before and after the drain and wastewater flowrate. Emission rates were to be measured for three gas sampling conditions:

- drain bagged using the vacuum method
- drain bagged using the blow-through method
- drain not bagged

In addition, organic vapor analyzer (OVA) measurements of total organic vapor concentrations were to be made to compare to USEPA's correlation equation for predicting emission rates from "other components" (USEPA, 1995a).

EXPERIMENTAL PROCEDURE

Analyte Selection and Characteristics

The compounds used during this study and their Henry's Law coefficients are presented in Table 2-1. Compounds encompassing a wide range of volatilities were selected and, where possible, compounds used in *Phase 1 Report: Estimation of Fugitive Emissions from Petroleum Refinery Process Drains* (American Petroleum Institute, 1996) (hereinafter called the "Phase 1 Report") were used in this task.

A Foxboro 108 OVA was used to indicate total organic concentrations in the gas phase. Since the instrument is calibrated using methane, gas phase concentrations indicated by the Foxboro 108 for compounds other than methane must be corrected using a response factor. Response factors for a variety of compounds are presented in the *1995 Protocol for Equipment Leak Emission Estimates* (USEPA, 1995a) (hereinafter called the "1995 EPA Protocol"). Therefore, analyte selection was influenced by the need to select VOCs where a response factor was available.

Table 2-1. Henry's Law Coefficients for Test Compounds

Compound	H (m^3_{liq}/m^3_{gas}) @ 25°C
Cyclohexane	7.17
Tetrachloroethylene	0.72
1,1,1-Trichloroethane (methyl chloroform)	0.71
Ethylbenzene	0.32
Toluene	0.26
o-Xylene	0.20

Apparatus

A schematic of the drain structure is presented on Figure 2-1. All materials were constructed of carbon steel. The drain funnel consisted of a standard six to four inch reducer. The influent wastewater line was 1 inch in diameter and discharged 1 inch above the plane of the drain opening. Thus, there was a 1 inch air gap between the inlet line and the plane of the drain opening. The discharge line was centered over the drain funnel and therefore, wastewater did not splash onto the edge of the funnel or drain pipe. The drain funnel was connected to a P-trap with a 4 inch diameter pipe. Figure 2-1 also includes the relative position of the OVA which was placed near to the water surface.

No Bag. The experimental set-up for the no bag condition was similar to that shown on Figure 2-1. The inlet to the OVA was located approximately 2 cm from the water surface. A suitable distance was maintained to exclude water from the OVA air sample (water will skew OVA results). The air sample flowrate to the OVA was maintained at approximately 1.75 L/min.

Vacuum Method. A schematic of the vacuum bag sampling apparatus is presented on Figure 2-2. The procedure is based on that outlined in the 1995 EPA Protocol (USEPA, 1995a).

The tent enclosure was constructed of Tedlar™ sheeting, obtained from cutting a 24" x 24" Tedlar™ sampling bag, and was secured around the drain structure using duct tape. The gas volume enclosed by the tent was estimated to be 3 L. Nickel-plated valves were used to connect the bag to a water manometer and a Viton^{TM} line leading to a cold trap. A third connection was made to the bag for allowing the OVA to sample the bag for gas phase contaminants. A small hole was cut in the bag and the OVA sample port put inside the tent enclosure. The inlet to the OVA was located approximately 2 cm from the water entering the tent. A suitable distance was maintained to prevent water from being included in the air sample.

Flow through the cold trap was monitored by a rotameter and a target flow rate of 4 L/min was maintained. The air sample flowrate required by the OVA ranged from 1 to 3 L/min and was preset by the supplier at 1.75 L/min. The total flowrate drawn through the tent enclosure from the ambient air was, therefore, 5.75 L/min. This air flowrate was in the range presented by the 1995 EPA Protocol (USEPA, 1995a) where typical flowrates were recommended to be 60 L/min or less. In addition, the flowrate through the cold trap was, for results comparison purposes, chosen to be the same as that used in the Phase 1 Report (American Petroleum Institute, 1996).

A second water manometer was located at the inlet side of the rotameter. A carbon adsorption tube was placed on the outlet side of the rotameter to eliminate potentially explosive conditions from reaching the vacuum pump which immediately followed the adsorption tube. The vacuum pump was used to draw air through the system. The vacuum in the bag was maintained at vacuums of 0.1" or greater.

Blow-Through Method. A schematic of the blow-through bag sampling apparatus is presented on Figure 2-3. The procedure is based on that outlined in the 1995 EPA Protocol (USEPA, 1995a). The procedure was identical to that utilized in the Phase 1 Report (American Petroleum Institute, 1996).

A cylinder of ultra-high purity nitrogen provided the blow-through gas. The nitrogen proceeded through a desiccant trap for moisture removal. The gas flowrate was measured using a rotameter before entering the tent enclosure.

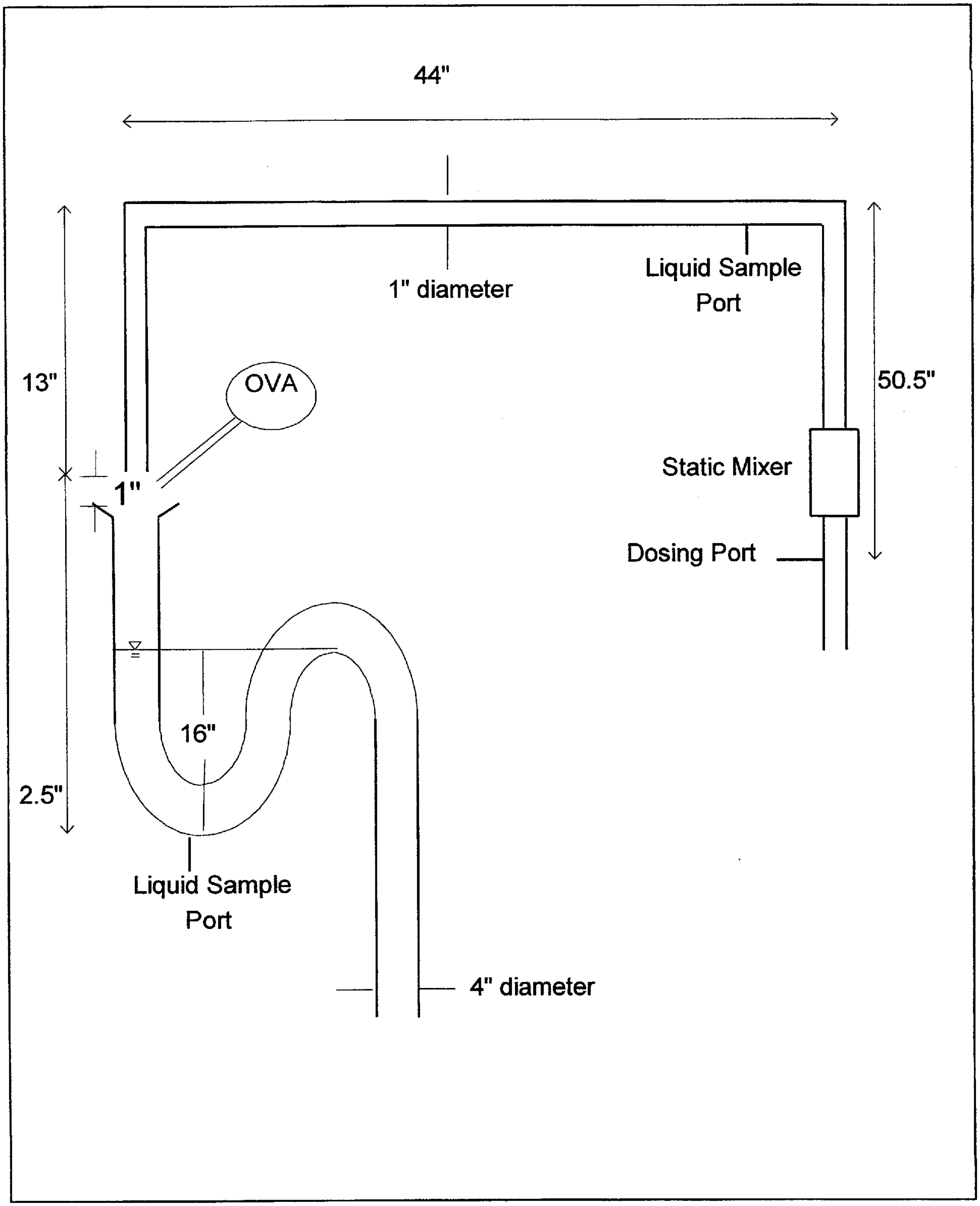

Figure 2-1. Schematic of Pilot Drain Structure

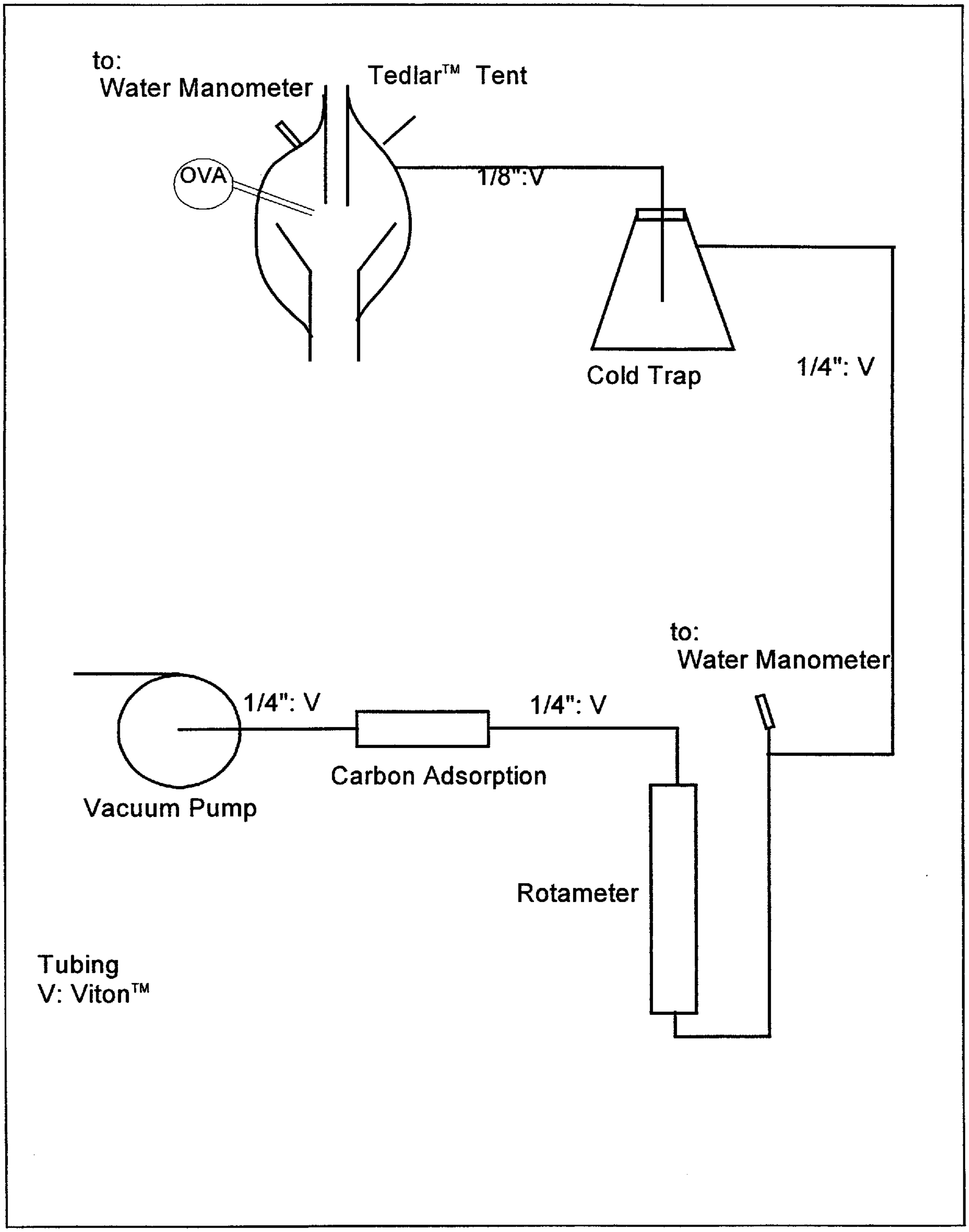

Figure 2-2. Vacuum Bag Apparatus

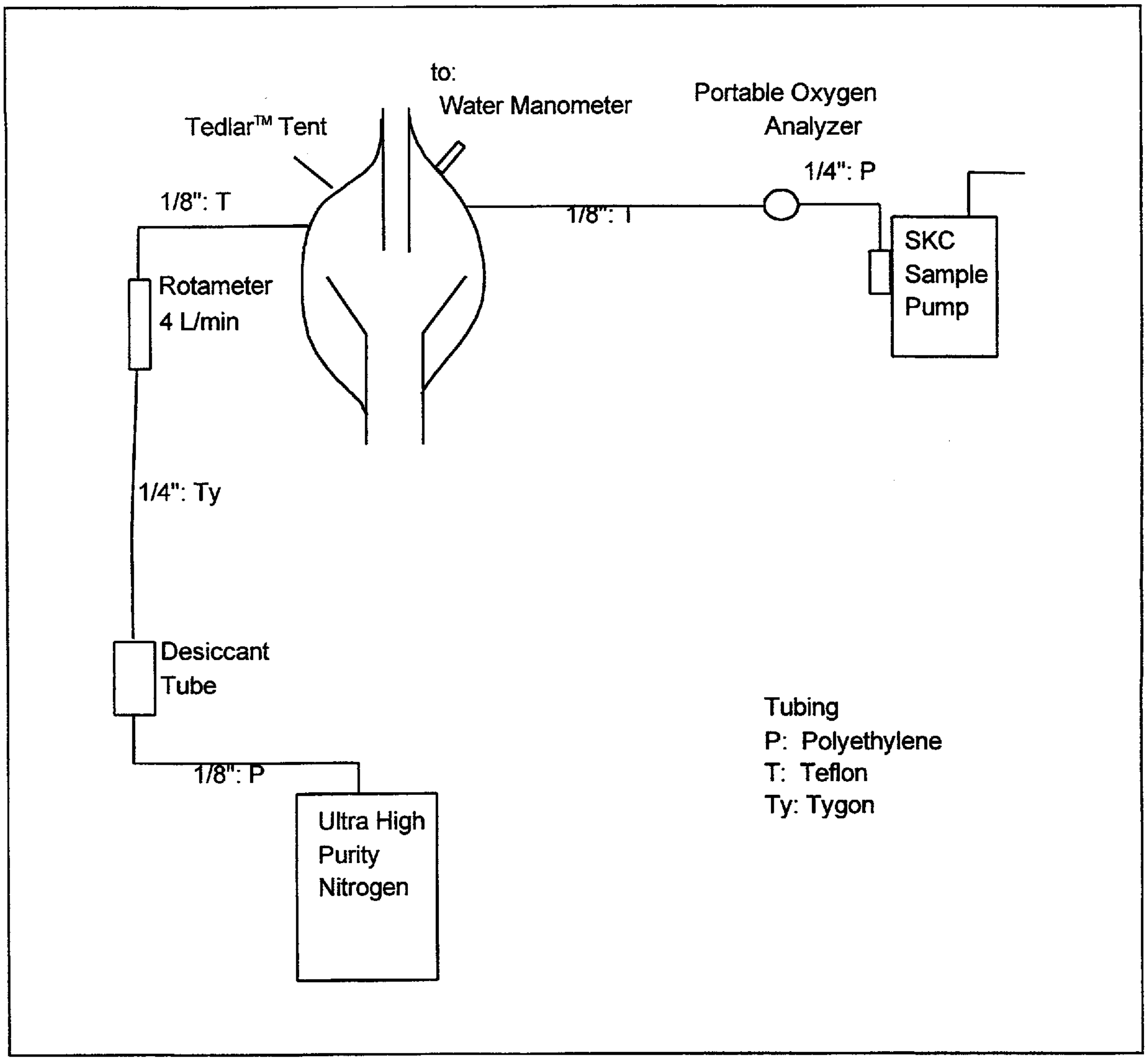

Figure 2-3. Pressure Bag Apparatus

The tent enclosure was constructed of Tedlar™ sheeting, obtained from cutting a 24" x 24" Tedlar™ sampling bag, and was secured around the drain structure using duct tape. The gas volume enclosed by the tent was estimated to be 3 L. Nickel-plated valves were used to connect the bag to a water manometer and a Viton™ line leading to an oxygen analyzer and ultimately to a SKC vacuum sample pump. In the Phase 1 Report (American Petroleum Institute, 1996), the SKC pump ensured that air from the tent enclosure was directed to the gas sampling apparatus. Although gas samples were not taken during this work, the SKC pump was used to maintain experimental conditions identical to those of the Phase 1 Report (American Petroleum Institute, 1996).

The nitrogen gas flowrate was controlled to 4 L/min, as used in the Phase 1 Report (API, 1995). The flow of the SKC pump was set at 2 L/min. The difference between the two flowrates (2 L/min) escaped from the tent enclosure to the ambient atmosphere and the lower flowrate of the SKC pump ensured a positive pressure within the tent enclosure was maintained. A tent enclosure pressure of 0.1" or greater was maintained for all blow-through experiments.

Due to the absence of oxygen in the tent enclosure, the use of nitrogen as a carrier gas in the blow-through procedure prevents potentially explosive conditions from occurring. In addition, the absence of oxygen prevents the use of the OVA since oxygen is required to maintain the flame used to ionize the compounds in the influent OVA gas stream.

Dosing Procedure

The target influent wastewater consisted of potable water, heated to 30° C. The flowrate was measured, prior to dosing, using a rotameter. The 6 compounds selected for dosing were dissolved in water and contained in a Tedlar™ bag. The bag contents were pumped into the influent water stream, at a controlled rate, through Viton™ tubing. The dosing bag collapsed upon itself as the contents were pumped, preventing the formation of headspace in the bag. The compounds were pumped into a vertical section of pipe because the full pipe encouraged mixing and provided a gas seal for the system. A static, helical mixer was located immediately downstream of the point where the dosing chemicals entered the influent line.

Wastewater Sampling and Analysis

All wastewater samples were collected in 40 mL amber, teflon, septum-top bottles, and analyzed using EPA method 624. Samples of the wastewater entering the drain were collected from a sample port in the horizontal section of the influent pipe, downstream of the dosing location. The contents of the P-trap were collected from a sample port at the bottom of the trap. Samples were collected 1 hour after dosing was initiated.

OVA Calibration

The OVA was calibrated using a two-point procedure using methane standards supplied with the instrument.

Experimental Schedule

Three sets of four experiments (no bag, vacuum bag and blow-through bag) were conducted, for a total of twelve experiments. The experiments were conducted in a random order (Table 2-2). The water flowrate was turned off and contaminant dosing suspended between experiments. A new Tedlar^{TM} enclosure was used for each experiment.

To ensure the experimental system was at a steady state condition, samples were taken one hour after the introduction of compounds to the influent wastewater. This time period was based on results from the Phase 1 Report (American Petroleum Institute, 1996).

Table 2-2. Experimental Schedule

Experiment Number	Date Test Conducted (1996)	Experimental Method
1	June 28	no bag
2	June 28	vacuum
3	June 29	blow-through
4	June 29	vacuum
5	June 29	no bag
6	June 30	no bag
7	June 30	blow-through
8	June 30	blow-through
9	June 30	no bag
10	June 30	blow-through
11	July 2	vacuum
12	July 2	vacuum

RESULTS

Sample Results for Each Experiment - Analysis of Duplicate Submissions

The analytical results for the twelve drain experiments are presented in Appendix A. For each experiment, between one and three samples were submitted of the influent water to the drain and the drain effluent. The number of samples were randomly submitted to meet the study budget. The influent and effluent sample averages and Coefficient of Variations (COV) for each experiment are presented in Appendix B. The COV was calculated as the ratio, expressed as a percentage, of the standard deviation of the samples to the sample average. If only one sample was submitted, the COV could not be determined. The majority (94%) of the COVs were less than 10% while more than half (52%) were less than 5%. These results indicate very good analytical repeatability.

Percentage Emissions

For each experiment, the average of the influent wastewater concentrations and the average of the effluent wastewater concentrations were used to calculate the percentage emissions from the drain. The percentage emissions were calculated using Equation 2-1.

$$\text{Emissions (\%)} = \left(\frac{C_{\text{influent}} - C_{\text{effluent}}}{C_{\text{influent}}} \right) \text{x } 100\% \qquad (2\text{-}1)$$

where:

C_{influent} = contaminant concentration before drain
C_{effluent} = contaminant concentration after drain

For each set of experiments, the average percentage emissions for the four experiments was calculated as well as the 95% confidence interval (two-tailed T-test) of the average. The results for each set of experiments are presented in Table 2-3, Table 2-4 and Table 2-5. In each of the tables, the compounds are listed from the most volatile (cyclohexane) to the least volatile (o-Xylene). Within each set of experiments, average percentage emissions were related to compound volatility (the greater the volatility, the greater the emissions).

A qualitative comparison of Table 2-4 and Table 2-5 suggests no consistent difference between emission rates for the set of experiments employing the vacuum and blow-through bagging procedures. A qualitative comparison of Table 2-3 to Table 2-4 and Table 2-5 suggests that emission rates were generally higher for the set of experiments employing no bag than the set of experiments using a bag (for the five less volatile compounds). There was no apparent difference for the most volatile compound, cyclohexane. Statistical analysis of the data is presented later.

The percentage emissions observed in the Phase 1 Report (American Petroleum Institute, 1996) (blow-through bag method only) and the blow-through bag results of this study are presented in Table 2-6. Cyclohexane and toluene, common compounds to both studies, had similar percentage emissions in both the Phase 1 Report (American Petroleum Institute, 1996) and this study.

Table 2-3. Summary of Drain Emissions (%) - No Bag

Compound	Expt 1	Expt 5	Expt 6	Expt 9	Avg	95% CI
Cyclohexane	43.6	34.8	37.0	39.7	38.8	±7.0
Tetrachloroethylene	36.8	31.2	33.9	32.4	33.6	±4.4
1,1,1-Trichloroethane	33.5	30.1	35.2	35.6	33.6	±4.6
Ethylbenzene	35.0	21.4	29.8	23.7	27.5	±11.3
Toluene	31.6	20.9	22.5	15.9	22.7	±12.0
o-Xylene	29.4	15.7	20.3	17.6	20.8	±11.1

Table 2-4. Summary of Drain Emissions (%) – Vacuum

Compound	Expt 2	Expt 4	Expt 11	Expt 12	Avg	95% CI
Cyclohexane	42.1	35.7	45.3	39.8	40.7	±7.4
Tetrachloroethylene	29.0	27.2	26.8	25.0	27.0	±3.0
1,1,1-Trichloroethane	27.7	32.1	33.3	21.8	28.7	±9.6
Ethylbenzene	20.5	17.0	14.8	15.2	16.9	±4.8
Toluene	19.3	11.2	13.4	16.2	15.0	±6.4
o-Xylene	17.0	14.2	9.9	13.2	13.6	±5.4

Table 2-5. Summary of Drain Emissions (%) - Blow-Through

Compound	Expt 3	Expt 7	Expt 8	Expt 10	Avg	95% CI
Cyclohexane	31.7	38.6	37.9	36.8	36.2	±5.7
Tetrachloroethylene	24.3	26.3	24.8	24.2	24.9	±1.8
1,1,1-Trichloroethane	21.6	16.5	29.5	31.2	24.7	±12.6
Ethylbenzene	14.2	12.2	16.8	23.5	16.7	±9.0
Toluene	16.1	11.5	12.4	17.0	14.2	±5.0
o-Xylene	11.0	9.4	15.1	10.8	11.6	±4.5

Table 2-6. Comparison of Blow-Through Bag Results for Phase 1 (American Petroleum Institute, 1996) and Phase 2 (Current Work)

Compound	H @ 25°C (m^3_{liq}/m^3_{gas})	Phase 1 Results[1] (% emissions)	Phase 2 Results[2] (% emissions)
Cyclohexane	7.17	39.0	36.2
Tetrachloromethane	1.23	26.4	–
Tetrachloroethylene	0.72	–	24.9
1,1,1-Trichloroethane	0.71	–	24.7
Ethylbenzene	0.32	–	16.7
Toluene	0.26	14.2	14.2
o-Xylene	0.20	–	11.6
1,4-Dichlorobenzene	0.13	7.6	–
Bromoform	0.02	2.0	–

1: Average of the three pilot scale experiments conducted in Phase 1 (Table 6-10 in Phase 1 Report - blow-through).
2: Average of the four blow-through experiments conducted in Phase 2.

Mass Emissions

The mass emissions for each experiment were determined using influent wastewater contaminant concentration, wastewater flowrate, and percentage emissions. The target wastewater flowrate set point for all of the experiments was 4 L/min with adjustment to the flow control device made when the indicated flowrate was greater or less than 5% (0.2 L/min) of the target flowrate (4 L/min). The equation used to calculate the mass emissions is presented in Equation 2-2 and results are presented in Table 2-7, Table 2-8, and Table 2-9.

$$\text{Mass Emissions} = C_o \times Q_o \times (PE / 100) \quad (2\text{-}2)$$

where:

mass emissions [µg/min] = contaminant mass transferred to the air

C_o = contaminant wastewater concentration before drain (µg/L)

Q_O = wastewater flowrate (4 L/min)

PE = contaminant percentage emissions

The total contaminant emission rate ranged from a low of 168.6 µg/min (blow-through experiment #3) to a high of 335.2 µg/min (no-bag experiment #6). Since emission rate is a function of contaminant concentration and contaminant percentage emissions and wastewater contaminant concentration varies, the emission rate varies. For example, cyclohexane, as indicated previously, had the greatest percentage emissions in all of the experiments and yet had the smallest mass emissions in all of the experiments. This is due to the lower influent cyclohexane wastewater concentration.

Table 2-7. Summary of Drain Emissions (µg/min) - No Bag

Compound	Expt 1	Expt 5	Expt 6	Expt 9
Cyclohexane	9.2	19.5	19.6	27.6
Tetrachloroethylene	51.7	66.4	72.0	71.2
1,1,1-Trichloroethane	55.6	73.8	84.8	101.2
Ethylbenzene	67.7	31.4	53.2	44.8
Toluene	70.5	57.4	57.6	46.0
o-Xylene	47.0	37.6	48.0	44.0
TOTAL	301.7	286.1	335.2	334.8

Table 2-8. Summary of Drain Emissions (µg/min) - Vacuum

Compound	Expt 2	Expt 4	Expt 11	Expt 12
Cyclohexane	8.2	21.8	39.8	32.8
Tetrachloroethylene	42.8	58.8	58.3	54.8
1,1,1-Trichloroethane	40.2	85.6	99.1	60.4
Ethylbenzene	30.6	25.6	32.5	28.4
Toluene	43.6	29.2	38.5	51.2
o-Xylene	29.2	35.2	24.5	33.6
TOTAL	194.6	256.2	292.7	261.2

Table 2-9. Summary of Drain Emissions (µg/min) - Blow-Through

Compound	Expt 3	Expt 7	Expt 8	Expt 10
Cyclohexane	7.2	24.4	26.4	24.2
Tetrachloroethylene	43.2	55.4	56.4	49.4
1,1,1-Trichloroethane	34.4	40.8	90.8	82.0
Ethylbenzene	23.0	20.6	41.6	48.6
Toluene	38.2	27.6	39.6	52.8
o-Xylene	22.6	22.0	41.6	27.0
TOTAL	168.6	190.8	296.4	284.0

Organic Vapor Analyzer Results

OVA Concentrations. The OVA was used during the set of experiments with no bag and vacuum bag. Ambient OVA and test OVA readings during the no bag and vacuum tests are presented in Table 2-10. Ambient OVA readings were recorded at various times before and after experiments. Since in the no bag and vacuum bag procedures ambient air is used as the carrier gas, the minimum expected OVA reading in the tent enclosure is the ambient OVA value. During the no bag and vacuum bag experiments this background concentration varied from 5 to 25 ppm. The reported test OVA values were recorded when the wastewater samples were collected (1 hour after commencing contaminant injection).

During the no bag experiments, OVA readings were generally near ambient levels (10 to 20 ppm). On two occasions (experiments 5 and 9) additional OVA readings were taken below the plane of the hub. These values were approximately 5 ppm greater than readings above the plane of the hub.

During the vacuum bag experiments, the increase in OVA readings ranged from 10 to 25 ppm. The variation in observed contaminant concentrations is postulated to be the result of variations in influent wastewater contaminant concentrations and instrument reading variation at these low values. During experiment 4, OVA readings of 25 ppm were recorded in the vacuum tent enclosure, prior to contaminant injection and with the wastewater flowing. This value is identical to ambient levels, indicating no reportable contamination of the air by the tent enclosure.

Mass Emissions. The OVA measurements for the vacuum bag experiments were converted to total mass emission rates following the procedure outlined in the 1995 EPA Protocol (USEPA, 1995a). The bagging procedure presented in the 1995 EPA Protocol (USEPA, 1995a) is reproduced in Appendix F and the total contaminant mass emissions calculated are presented in Table 2-11. In addition to the OVA based mass emissions, Table 2-11 contains the wastewater mass balance based emission rates and the ratios of the OVA to wastewater determined mass emissions. The OVA indicated greater emission rates ranging from a low of 120% to a high of 180% of that indicated by the wastewater mass balance method.

The mole fractions required for the calculation of the contaminant mixture's collective molecular weight and response factor were based on the wastewater analytical results.

Although OVA measurements for the no-bag condition were collected, the mass emission rate for the no-bag condition can not be determined due to an unknown airflow rate. OVA measurements for the blow-through method were not collected since the carrier gas (nitrogen) did not contain oxygen and, therefore, the OVA ionization flame could not ignite.

Table 2-10. Observed OVA Readings

Experiment	OVA Readings* (ppm)		Increase in OVA Reading
	Background	During Experiment	
No Bag Experiments			
1	10	10	0
5	18	20 (25*)	2
6	10	10	0
9	15	15 (20*)	0
Vacuum Bag Experiments			
2	10	20	10
4	25	40	15
11	5	30	25
12	10	25	15

••••The reported test OVA values were recorded when the wastewater samples were collected (1 hour after commencing contaminant injection).
*: Reading taken below the plane of the hub.

Table 2-11. Total Drain Emissions Based on OVA Measurements - Vacuum

Experiment	Total Mass Emissions (µg/min)		Ratio of OVA to Wastewater Methods
	OVA Based	Wastewater Based	
2	240.6	194.6	1.2
4	356.3	256.2	1.4
11	519.2	292.7	1.8
12	306.8	261.2	1.2

Statistical Analysis of Results

In order to determine if there is a statistical difference between the bagging methods, a statistical T-test was conducted. The first statistical test was conducted to determine if there is a difference between the vacuum bag and blow-through bag values. For the T-test, the average emission values for each of the experiments (4 no bag and 4 vacuum bag) were used.

The results are presented in Table 2-12 and indicate that for all of the compounds, values were not statistically different at a significance level of 0.1.

The second statistical test was conducted to determine if the vacuum bag and blow-through results were different from those observed during the no bag method. Since no difference was found between the vacuum and blow-through methods, their results were combined and then compared to the no bag method. The results of the test are presented in Table 2-13. For the five less volatile compounds, analysis indicates that the percentage emissions were statistically different at a significance level of 0.1. For the most volatile compound, cyclohexane, the percentage emissions were not statistically different at a significance level of 0.1.

Table 2-12. Comparing Vacuum and Blow-Through Methods

Compound	H (m^3_{liq}/m^3_{gas}) @ 25°C	Vacuum and Blow-through Experiment Averages Are The Same ?[1] (Y or N) (level of significance = 0.1)[2]
Cyclohexane	7.17	y
Tetrachloroethylene	0.72	y
1,1,1-Trichloroethane	0.71	y
Ethylbenzene	0.32	y
Toluene	0.26	y
o-Xylene	0.20	y

1: Based on 2-sided T-test.
2: corresponds to $t_{.95}$.

Table 2-13. Comparing Combined Vacuum and Blow-Through Methods To No Bag Method

Compound	H (m^3_{liq}/m^3_{gas}) @ 25°C	Bag and No Bag Experiment Averages Are The Same?[1] (Y or N) (level of significance = 0.1)[2]
Cyclohexane	7.17	y
Tetrachloroethylene	0.72	n
1,1,1-Trichloroethane	0.71	n
Ethylbenzene	0.32	n
Toluene	0.26	n
o-Xylene	0.20	n

1: Based on 2-sided T-test.
2: Corresponds to $t_{.95}$.

DISCUSSION OF RESULTS

Results indicate that there was no statistical difference in percentage emissions between the vacuum and blow-through drain bagging protocols. Results indicate that, for the five least volatile compounds, percentage emissions were statistically greater for the drain with no bag than for the drain enclosed by a bag. For the most volatile compound, cyclohexane, there was no difference.

The above observation may be consistent with an air entrainment mechanism. In the case of a drain with no bag enclosure, the air in the area of the drain hub would likely be continuously swept clean, (i.e., contaminant gas phase concentration equals zero). The contaminant mass transfer driving force (difference between the equilibrium and actual gas concentrations) from the liquid in the P-trap to the rising air bubble is thereby maximized. In the case of the bagged drain, the limited gas flow through the enclosure likely results in headspace gas, inside the bag contaminated with the organic compounds, being drawn back down into the water stream. Since the gas contains contaminants, the mass transfer driving force from the liquid to the rising gas bubble is reduced as compared to the non-bagged condition where the gas contains no contaminants. As contaminant volatility increases, more contaminant can be transferred from the liquid to the gas before equilibrium conditions are obtained. As a result, the driving force for higher volatility compounds will not be reduced to the same extent as that for low volatility compounds. Higher volatile compounds, therefore, will be less sensitive to the effects of recirculated gas. The impact of the bag on emissions may be minimized by increasing the air flowrate through the bag although this has not received experimental verification.

3. PILOT SCALE DETERMINATION OF STRIPPING EFFICIENCIES

The objective was to develop emission factors for refinery process drains. The emission factors developed estimate drain emissions as a function of compound volatility under different operating conditions for both active and inactive drains. In addition to drain emission factors, this study:

- compared aligned and misaligned drain emissions
- repeated three experiments conducted at the University of Texas for a pilot scale verification of bench scale work
- compared drain mass emissions as a function of Organic Vapor Analyzer (OVA) values to those reported in literature.

EXPERIMENTAL PROCEDURE

Analyte Selection and Characteristics

The compounds used during this study and their Henry's Law coefficients are presented in Table 3-1. Compounds encompassing a wide range of volatilities were selected. Since the emission tables to be developed in this work were not compound specific but rather volatility dependent, the selection of compounds were based on availability and the ability of the OVA to detect the compounds.

A Foxoboro 108 OVA was used to indicate total organic compounds (TOCs) in the gas phase. Since the instrument is calibrated using methane, gas phase concentrations indicated by the Foxboro 108 must be corrected using a response factor. Response factors were obtained from the 1995 EPA Protocol (USEPA, 1995a). If a contaminant's response factor was not available in the 1995 EPA Protocol, the manufacturer's response factor was used.

Table 3-1. Henry's Law Coefficients for Test Compounds

Compound	H (m^3_{liq}/m^3_{gas}) @ 25°C
Cyclohexane	7.17
Tetrachloromethane	1.23
Tetrachloroethylene	0.72
Ethylbenzene	0.32
Toluene	0.26
o-Xylene	0.20
1,4-Dichlorobenzene	0.13
Bromoform	0.02

Experimental Apparatus

Two distinct experimental drain structures were used during this study. Two sets of experiments were conducted on a drain structure similar to that used in previous API work (American Petroleum Institute, 1996) conducted by Enviromega. The first of these used a misaligned discharge configuration and the second used an aligned discharge configuration. The drain structure was then modified to duplicate experiments conducted at the University of Texas. Each experimental apparatus is discussed separately.

Emission Factor Drain Structure. A schematic of the emission factor drain structure is presented on Figure 3-1. All materials were constructed of carbon steel. The drain funnel consisted of a standard six to four inch floor drain. The influent wastewater line was one inch in diameter and discharged four inches and nine inches above the plane of the drain opening. The floor drain was connected to a liquid seal trap (6.8L) (often referred to as a P-trap or J-trap) using a 4 inch diameter pipe. As indicated on Figure 3-2, the discharge line was off-center over the drain funnel and discharged onto the angular section of the floor drain.

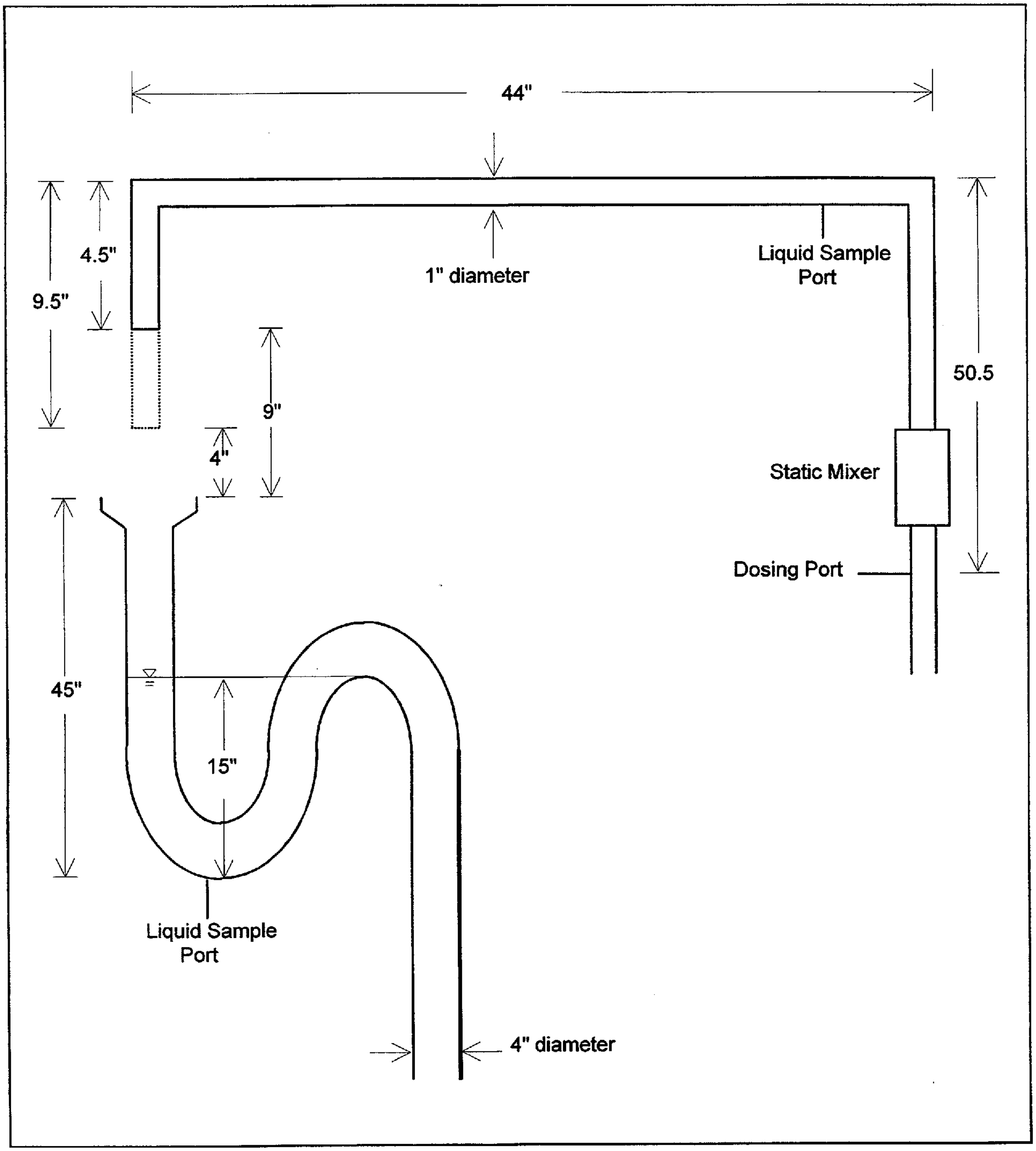

Figure 3-1. Drain Emission Factor Drain Structure

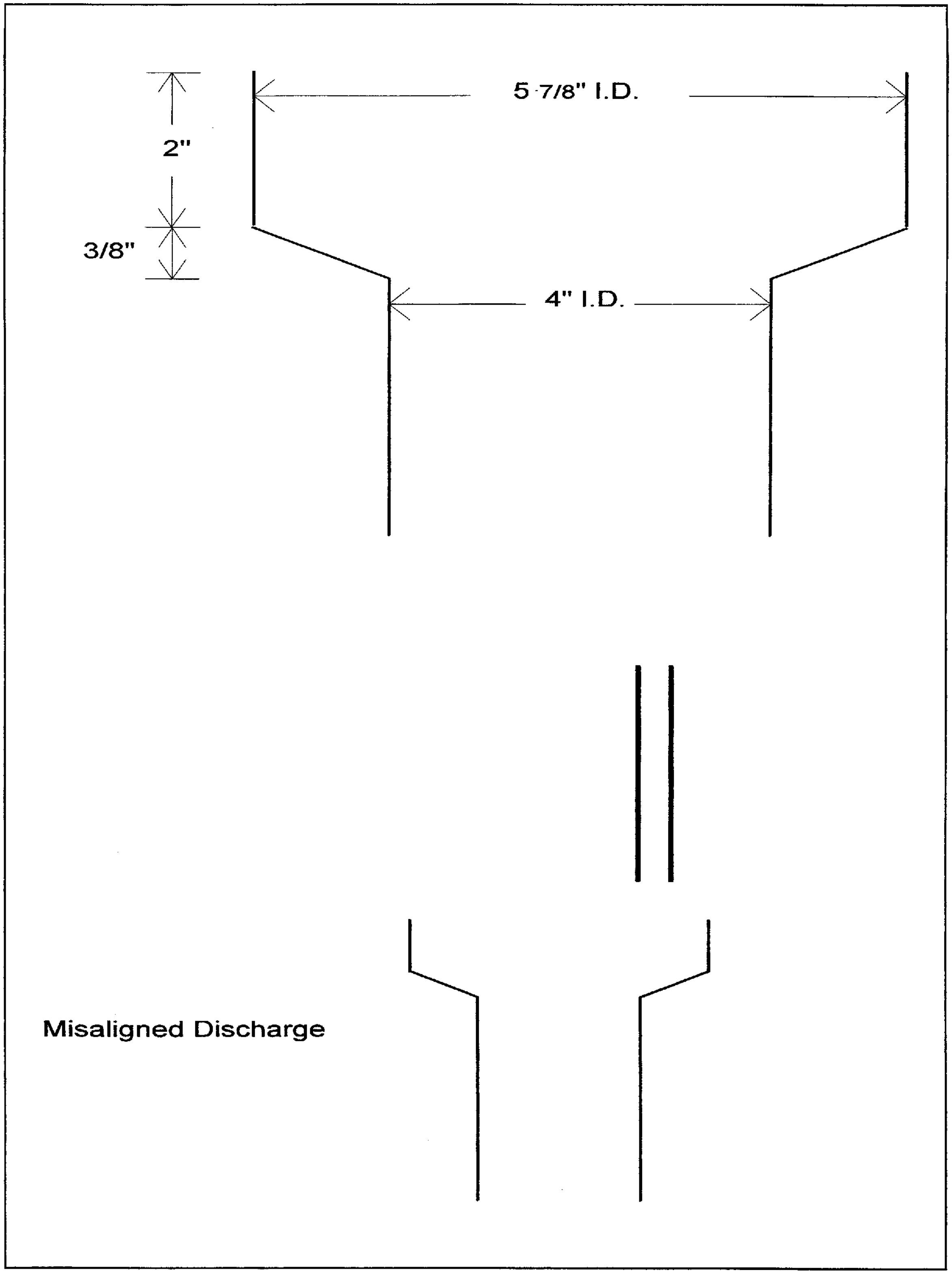

Figure 3-2. Drain Emission Factor Hub Structure

Emission Factor Drain Structure - No Bag. The experimental set-up for the no-bag condition was similar to that shown on Figure 3-1 and Figure 3-2. The OVA was placed above the top of the drain hub and located a horizontal distance of approximately 2 to 5 cm from the discharge water stream. A suitable distance was maintained to exclude water from the OVA sample. The air sample flowrate to the OVA was maintained at approximately 1.75 L/min.

Emission Factor Drain Structure - Vacuum Method. A schematic of the vacuum bag sampling apparatus is presented on Figure 3-3. The procedure is based on that outlined in 1995 EPA Protocol (USEPA, 1995a)

The tent enclosure was constructed of Tedlar™ sheeting, obtained from cutting a 24" x 24" Tedlar™ sampling bag, and was secured around the drain structure using duct tape. The gas volume enclosed by the tent was estimated to be 3 L (this does not include the drain throat volume). Nickel-plated valves were used to connect the bag to a water manometer and a Viton™ line leading to a cold trap. A third valve was used as the sampling port for the OVA.

Flow through the cold trap was monitored by a rotameter and a target flow rate of 4 L/min was maintained. The air sample flowrate required by the OVA can range from 1 to 3 L/min and was preset by the supplier at 1.75 L/min. The total flowrate drawn through the tent enclosure from the ambient air was, therefore, 5.75 L/min. This air flowrate was in the range presented by the 1995 EPA Protocol (USEPA, 1995a) where typical flow rates were recommended to be 60 L/min or less. In addition, the flowrate through the cold trap was, for results comparison purposes, chosen to be the same as that used during the Phase 1 and Phase 2 Task 2 work (4 L/min).

A carbon adsorption tube was placed at the inlet to the pump to eliminate potentially explosive conditions from reaching the vacuum pump. The vacuum pump was used to draw air through the system. The vacuum in the bag was maintained at vacuums of 0.1" of water or greater.

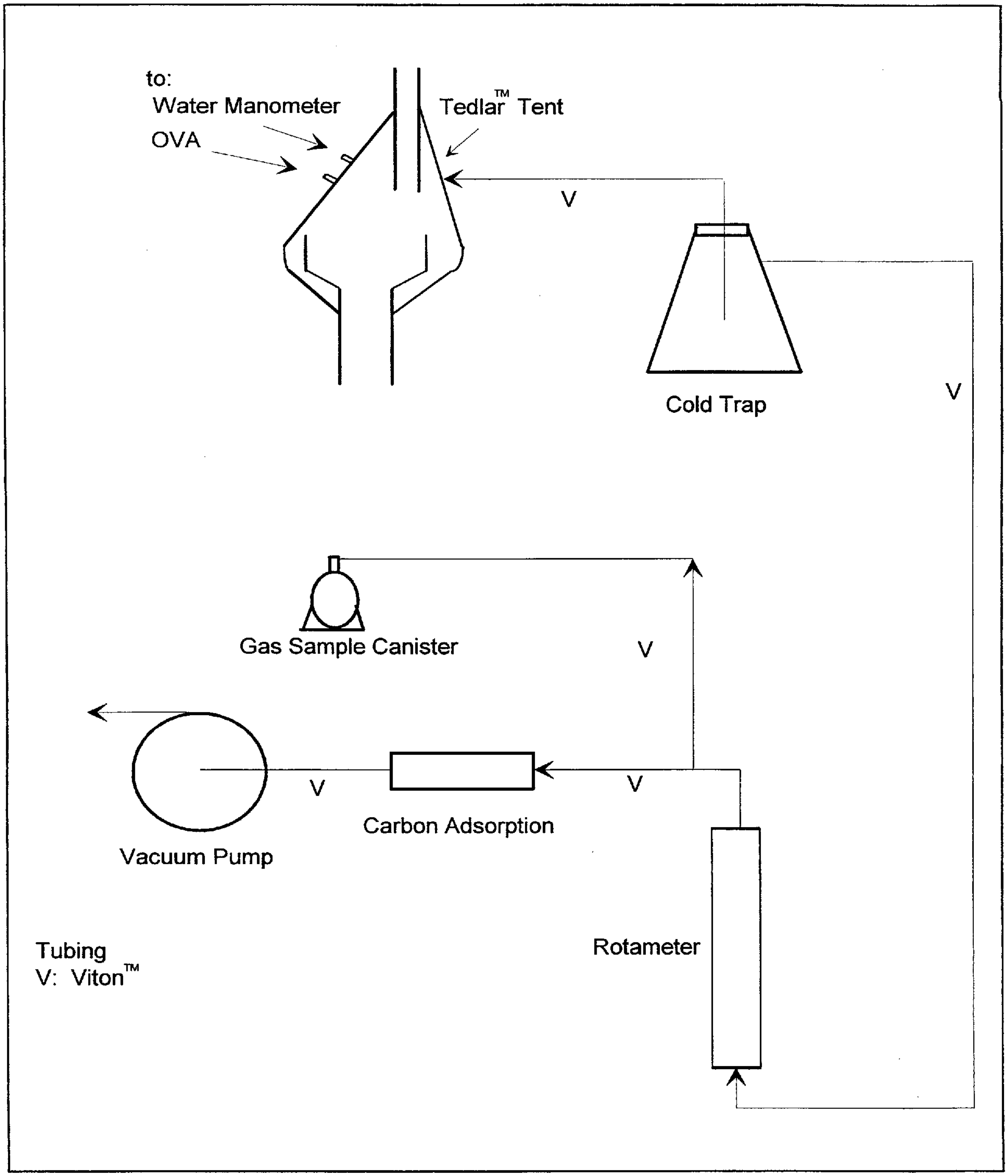

Figure 3-3. Drain Emission Structure - Vacuum Bag

Aligned Drain Structure. The aligned drain structure was the same as that indicated on Figure 3-1. The OVA was placed above the plane of the top of the drain hub. It was a horizontal distance of approximately 2 to 5 cm from the discharge water stream. A suitable distance was maintained to exclude water from the OVA sample. The air sample flowrate to the OVA was maintained at approximately 1.75 L/min. Water from the discharge pipe entered the center of the drain as indicated on Figure 3-4.

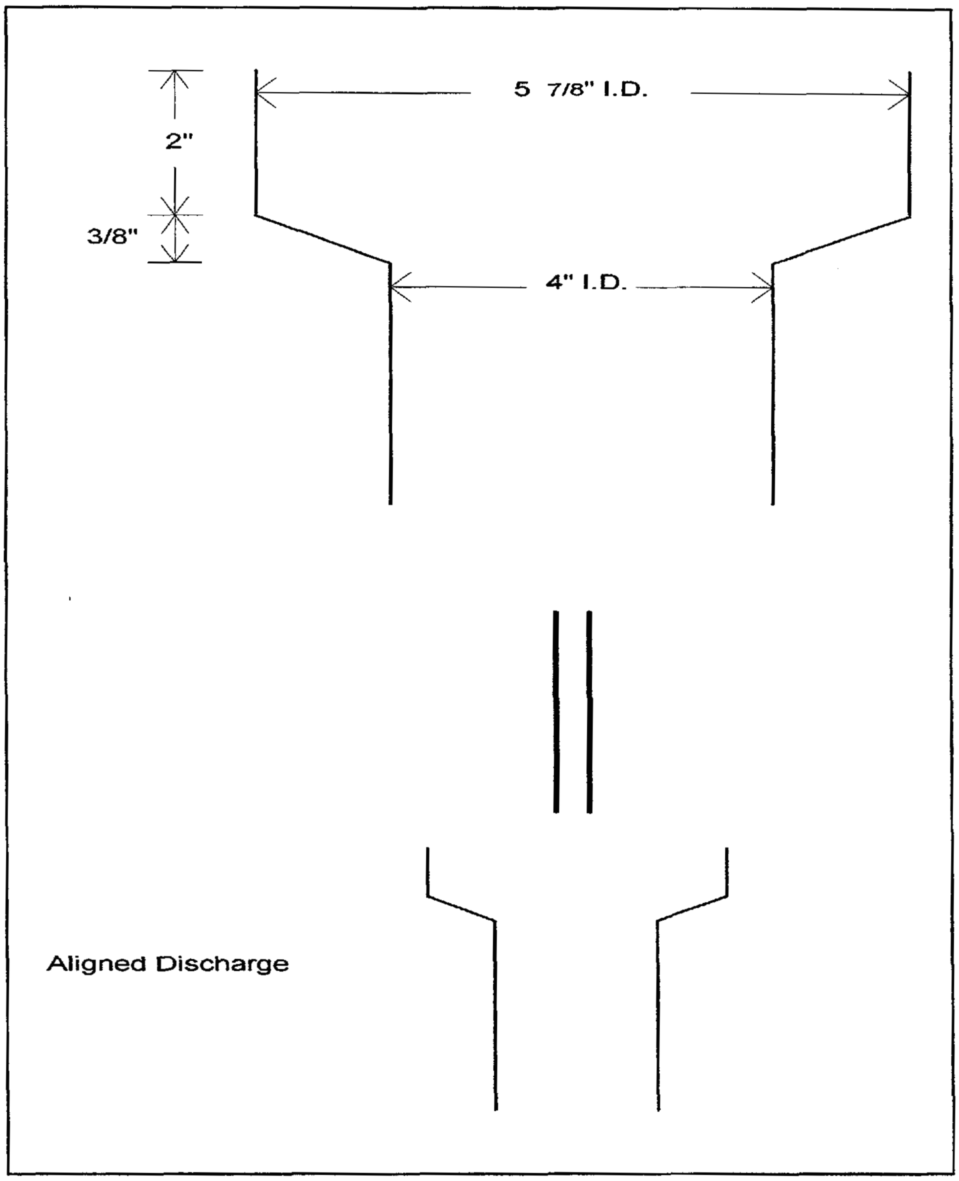

Figure 3-4. Aligned Drain Discharge

University of Texas Drain Structure. The drain structure used for the emission factor and aligned discharge experiments was modified in order for it to resemble the drain structure used during some of the experiments conducted at the University of Texas. A schematic representation of the drain structure used is presented on Figure 3-5. The exposed liquid film height was maintained at 10 cm (3.9 inches) and the liquid film fall height at approximately 31 cm (12.2 inches). Additional experiments were conducted with a liquid fall height of 62 cm (24.4 inches). These experiments were not conducted at the University of Texas and were included to examine the effect of drop height on percentage emissions. No OVA measurements were made with this drain structure.

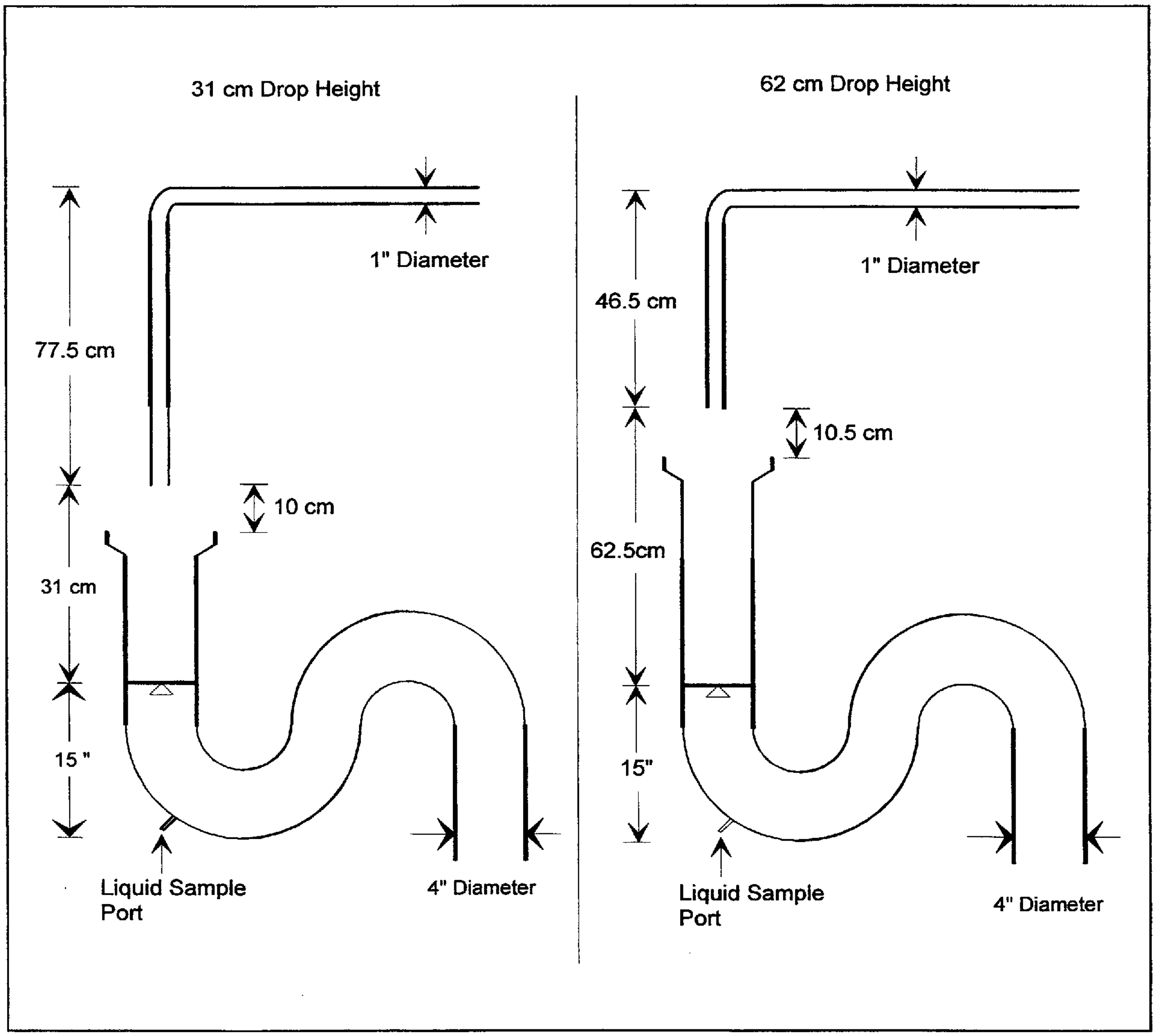

Figure 3-5. Replication of University of Texas Drain Structure

Dosing Procedure

The eight compounds selected for dosing were dissolved in water and contained in a Tedlar™ bag. The bag contents were pumped into the influent water stream, at a controlled rate, through Viton™ tubing. The dosing bag collapsed upon itself as the contents were pumped, preventing the formation of headspace in the bag. The compounds were pumped into a vertical section of the pipe because the full pipe encouraged mixing and provided a gas seal for the system. A static, helical mixer was located immediately downstream of the point where the dosing chemicals entered the influent line.

A storage tank was used to contain the water used during an experiment. Prior to injecting contaminants, the storage tank was dechlorinated (conversion of potentially oxidizing chlorinated compounds to chloride ions) using sodium sulphite. The total chlorine was monitored using a portable HACH kit (model CN-70T) with a minimum reportable detection limit of 0.02 mg/L.

Sample Analysis

All wastewater samples were collected in 40 mL amber, teflon, septum-top bottles, and analyzed using EPA method 624. Samples of wastewater entering the drain were collected from a sample port in the horizontal section of the influent pipe, downstream of the dosing location. The contents of the P-trap were collected from a sample port at the bottom of the trap.

All gas phase samples were collected in four liter evacuated canisters and analyzed using EPA method TO-14. By utilizing a stainless steel capillary tube to restrict flow, each canister sample was collected over a period of approximately forty-five minutes.

During all experiments, three liquid samples were collected at each sampling port. Either one or two samples were submitted to the laboratory for analysis with the third kept as a back-up. During the bagged experiments, one sample was generally collected. On two occasions, a second gas sample was collected and submitted. On one occasion, a background ambient air sample was collected and submitted.

OVA Calibration

The OVA was calibrated using a two-point procedure using methane standards (100 ppmV and 10,000 ppmV).

Experimental Plan and Methodology

The experimental plan and methodology for the drain emission factor study, aligned drain emissions and the replication of the University of Texas experiments are each discussed separately in this section.

Drain Emission Factor Study. During the drain emission factor set of experiments the following process variables were altered:

- water discharge velocity (water flow rate)
- discharge height above drain
- discharge water temperature.

The experimental matrix is presented in Table 3-2. A total of nine sets of experiments are indicated with each set consisting of a bag and unbagged experiment. With the exception of the inactive drain experiments, each experiment was first conducted under the bagged condition and then immediately repeated in the non-bagged condition.

The variations in process conditions outlined in Table 3-2 are explicitly identified in Table 3-3. The wastewater velocities presented in Table 3-3 represent flow rates of 2 and 8 L/min through the 1 inch diameter discharge pipe. It should be noted that for the inactive drain the low temperature (20 °C) was the target temperature, however, since the drain was left for a period of time (24 hours), the actual temperature was near the ambient temperature (20 to 28 °C).

With the exception of the inactive drain, water and gas samples were collected 1 hour after contaminant dosing was initiated. For the inactive drain experiments, the sampling procedure is presented in Table 3-4. During these experiments, dosing was initiated and liquid samples were collected approximately one half hour later. This first sample was considered time 0. Additional liquid samples were collected at times 1, 4, 8, and 24 hours. Gas samples for the bagged inactive drain were collected at 1 and 4 hours.

Table 3-2. Drain Emission Factor Experimental Plan

		% Emissions			
		Low Velocity		High Velocity	
		Bagged	Non-bagged	Bagged	Non-bagged
Low Temperature	Low Height	x	x	x	x
	High Height	x	x	x	x
High Temperature	Low Height	x	x	x	x
	High Height	x	x	x	x
Inactive Drain (low temp)		x x (bagged and unbagged)			

Table 3-3. Drain Emission Factor Experimental Process Variation

Condition	Value
Discharge Temperature [°C]	
Low	20
High	40
Discharge Velocity [L/(cm^2 min)]*	
Low	0.39
High	1.56
Wastewater Discharge Height Above Hub of Drain (inches)	
Low	4
High	9
Wastewater Discharge Alignment With Drain	
Misaligned	discharge onto sloped funnel portion
*:Values based on wastewater flowrate (2 and 8 L/min) divided by nominal cross sectional area of discharge pipe (dia. nominal = 1", cross-sectional surface area approximately 5.1 cm^2)	

Table 3-4. Inactive Drain Sampling Schedule

Time (hr)	Sample Collection	
	Liquid	Gas
0	x	
1	x	x
4	x	
8	x	
24	x	x

Aligned Drain Emissions. As indicated previously, all of the drain emission factor experiments were conducted using a misaligned discharge to the drain hub. In order to investigate the difference in emissions between aligned and misaligned drains, two additional experiments were conducted. These experiments had identical process conditions to two of the misaligned experiments and were unbagged experiments. The experiments were conducted to duplicate misaligned experiments with the following conditions:

- low temperature: 20 °C
- high discharge velocity: 1.56 L/cm^2/min (8 L/min; discharge pipe diameter = 1 inch)
- low and high discharge height: 4 and 9 inches (10 cm, 22.5 cm)

Duplication of University of Texas Experiments. Three experiments conducted at the University of Texas were replicated using the modified drain structure. The process conditions are presented in Table 3-5 and represent the University of Texas experiments identified as S1, S2, and S5. In addition to the three experiments conducted by the University of Texas, Table 3-5 indicates the two experiments conducted which examine the effect of drop height. Drop height is defined as the distance from the point of discharge to the surface of the water in the liquid sealed trap. In these experiments the drop height was increased from 31 cm (University of Texas drop height) to 62 cm. All of the experiments used an aligned drain and the exposed liquid film length was maintained at 10 cm. Exposed liquid film length is defined as the distance from discharge to the plane of the drain hub.

Table 3-5. University of Texas Replication Experiments - Process Conditions

University of Texas Experiments		
Temperature (°C)	Drop Height (cm)	Discharge Flow rate[1] L/min [L/cm^2/min]
24 (S1)[2]	31	3.8 [0.75]
24 (S2)[2]	31	7.6 [1.49]
24(S5)[2]	31	11.4 [2.23]
Additional Experiments (variation in drop height)		
24	62	3.8 [0.75]
24	62	11.4 [2.23]

1: discharge pipe diameter = 1 inch
2: "S1," "S2," and "S5" refer to the experiment numbers designated by the University of Texas. (See Table 3-9 of API Publication Number 4678.)

Experimental Schedule

All experiments were conducted during the months of June and July of 1997. The identification of individual experiments, test dates and experimental conditions are presented in Table 3-6. For the drain emission factor set of experiments, a random order of the tests was conducted. In addition, three of the drain emission factor experiments were repeated. The drain emission factor experiments were identified as "a" if they were bagged and "b" if they were non-bagged.

Table 3-6. Experimental Schedule

Drain Emission Factor Experiments ("a" bagged; "b" non-bagged)				
Experiment	Date Test (1997)	Temperature (L= low, H =high)	Discharge Velocity (L= low, H =high)	Discharge Height (L= low, H =high)
1a, 1b	June 30	L	H	L
2a, 2b	July 2	L	L	H
3a, 3b	July 3	H	L	H
4a, 4b	July 4	H	H	L
5a, 5b	July 7	H	L	L
6a, 6b	July 8	L	L	L

Table 3-6. Experimental Schedule

Drain Emission Factor Experiments ("a" bagged; "b" non-bagged)				
Experiment	Date Test (1997)	Temperature (L= low, H =high)	Discharge Velocity (L= low, H =high)	Discharge Height (L= low, H =high)
7a, 7b	July 11	L	H	H
8a, 8b	July 14	H	H	H
9a	July 17	L	none	None
9b	July 9	L	none	None
Replicate 3b (non-bagged)	July 18	H	L	H
Replicate 5b (non-bagged)	July 18	H	L	L
Replicate 1a (bagged)	July 21	L	H	L
Aligned Drain Emission Experiments (non-bagged)				
A1	July 21	L	H	H
A2	July 21	L	H	L
Replication of University of Texas Experiments (non-bagged)				
		Temperature (^{o}C)	Discharge Velocity (L/min)	Drop Height (cm)
UT1	July 30	24	3.8	31
UT2	July 30	24	7.6	31
UT3	July 30	24	11.4	31
UT4	July 31	24	3.8	62
UT5	July 31	24	11.4	62

RESULTS

Analytical results for all of the experiments (liquid and gas phase concentrations) are presented in Appendix C. Results for each of the experimental tests (i.e., drain emission factors (misaligned), aligned drain and University of Texas replication) are presented separately.

Duplicate Sample Analysis

As indicated in Appendix C where the analytical data are presented, duplicate samples were submitted for quality assurance and quality control. A total of 15 duplicate liquid samples and 2 duplicate gas samples were submitted. As a percentage of the average of the two values, the deviation from the mean was less than 5% in 73% of the cases. The deviation from the mean was between 5 and 10% in 19% of the cases.

Discharge Column of Water Description

As part of this study a number of flow velocities through the discharge pipe to the drain were examined ranging from a low of 0.39 L/(cm^2 min) to a high of 2.23 L/(cm^2 min). These velocities correspond to flow rates through the 1 inch diameter pipe of 2 L/min and 11.4 L/min, respectively.

At low flow rates (2 L/min), the water exited from a small section of the pipe and substantial side streams of water were observed leaving the liquid film as it proceeded towards the drain.

At flow rates near 4 L/min, two modes of discharge were observed. In the first mode, the water was in contact with the entire inner circumference of the discharge pipe. In the second mode, the discharge water was in contact with only a portion (approximately 1/2) of the inner pipe circumference. During the stream's transition between the two modes considerable sidestreams of water were observed.

At flow rates near 8 L/min, the discharge stream was observed to be generally solid. The stream, however, would regularly break up and water would spray out from the sides of the stream.

At the largest flow rates tested (11.4 L/min), the discharge stream was a solid stream and no side streams were observed.

In summary, the discharge liquid film was observed to be disintegrated at flows below 8 L/min and solid at flow rates near 11 L/min.

It should also be noted that during all experiments, there was no entrained air carried through the water seal trap discharge. This was determined by cutting a hole in the p-trap at its discharge side and observing no air bubbles coming up from the water seal.

Drain Emission Factors Experiments (misaligned drain)

As indicated previously, all of the analytical results are presented in Appendix C. Sample results include liquid concentrations (p-trap influent and effluent) and gas concentrations (bagged experiments). During the inactive drain experiments liquid temperatures in the drain were recorded when liquid samples were collected. The temperatures recorded are presented in Table 3-7.

Table 3-7. Inactive Drain Liquid Temperature

Time (hr)	Temperature (°C)	
	Bagged	Non-bagged
0	22.5	23.5
1	24.0	23.5
4	28.5	22.0
8	31.0	22.0
24	28.5	22.5

Calculation of Experimental Percentage Emissions. For the active drain experiments and under bagged conditions, the percentage emissions were based on the influent liquid mass flow and gas phase concentrations. Under these conditions, the percentage emissions were calculated as indicated in Equation 3-1. The gas phase concentrations were used since they were considered to provide the most accurate measurement of gas emissions and hence the percentage emissions.

$$\text{Emissions (\%)} = \frac{Q_{gas}C_{gas}}{Q_{liquid}C_{liquid}} \times 100\% \qquad (3\text{-}1)$$

where:

Q_{gas} = flow rate of gas drawn through bag [L/min]
C_{gas} = gas phase concentration [μg/L]
Q_{liquid} = flow rate of liquid through p-trap [L/min]
C_{liquid} = influent liquid phase concentration [μg/L]

For the active drain experiments and under non-bagged conditions (no gas phase concentrations available), the percentage emissions were based on the average influent and effluent liquid phase concentrations. The percentage emissions were calculated using Equation 3-2.

$$\text{Emissions } (\%) = \left(\frac{C_{\text{influent}} - C_{\text{effluent}}}{C_{\text{influent}}} \right) \times 100\% \tag{3-2}$$

where:

C_{influent} = influent liquid phase concentration [µg/L]
C_{effluent} = effluent liquid phase concentration [µg/L]

For the inactive drain experiments and under bagged conditions, the emissions were calculated using Equation 3-3. The equation indicates the percent of the contaminant mass in the p-trap that is emitted per minute. This value is then converted to units of percent per hour. The gas phase concentrations were used since they were considered to provide the most accurate measurement of gas emissions and hence the percentage emissions.

$$\text{Emissions } (\% / \text{min}) = \left(\frac{Q_{\text{gas}} C_{\text{gas}}}{V_{\text{liquid}} C_{\text{liquid}}} \right) \times 100\% \tag{3-3}$$

where:

Q_{gas} = flow rate of gas drawn through bag [L/min]
C_{gas} = gas phase concentration [µg/L]
V_{liquid} = volume of liquid in p-trap [measured to be 6.8L]
C_{liquid} = liquid phase concentration in trap [µg/L]

For the inactive drain and under non-bagged conditions, only liquid phase concentrations were available. The percentage emissions per unit time was based on the liquid concentrations at two different times and was determined using Equation 3-4 and comes from successive substitution.

$$C_{liq,n} = t\, C_{liq,m} (1-x)^{n-m} \tag{3-4}$$

where:

$C_{liq,n}$ = liquid phase concentration [µg/L] at later time n [hr]
$C_{liq,m}$ = liquid phase concentration [µg/L] at earlier time m [hr]
x = emission rate between $C_{liq,m}$ and $C_{liq,n}$ [(% emissions/hr) / 100]
n-m = time interval between $C_{liq,m}$ and $C_{liq,n}$ [hr]
t = time [hr]

The calculated value of x, converted to a percentage, indicates the percent of the contaminant mass in the trap that is emitted per hour. The unit of hour was used since samples were collected at 0, 1, 4, 8, and 24 hours.

Emission Factor Tables. The percentage emissions for the emission factor experimental matrix were calculated based on the formulas presented earlier. A matrix of emission factors for each contaminant is presented in Appendix D. Table 3-8 to Table 3-11 present the emissions based on volatility range. The volatility ranges as expressed by Henry's Law Coefficient (ratio of equilibrium gas to liquid concentrations; Hc) values are:

- $1.23 \leq Hc \leq 7.17$ (highly volatile)
- $0.32 \leq Hc < 1.23$ (volatile)
- $0.13 \leq Hc < 0.32$ (moderately-volatile)
- $0.02 \leq Hc < 0.13$ (semi- volatile to moderately-volatile).

For each volatility range, the low and high percentage emissions for that group are presented.

The time intervals used to indicate the inactive drain under non-bagged conditions were 0-1 hours, 0-4 hours, 0-8 hours, and 0-24 hours. These time ranges were arbitrarily chosen to represent the emission factor for the non-bagged condition. For all of the tables, negative emissions are reported as zero.

Table 3-8. Emission Factors: $1.23 \leq Hc \leq 7.17$

Hc Range: $1.23 \leq Hc \leq 7.17$ (highly volatile)		% Emissions			
		Low Velocity		High Velocity	
		Bagged	Non-bagged	Bagged	Non-bagged
Low Temp	Low Height	15 - 17	56 - 57	29 -44	32 – 32
	High Height	18 - 21	51 - 56	28 -48	28 – 33
High Temp	Low Height	21 - 26	64 - 71	43 - 58	35 – 57
	High Height	31 - 50	59 - 66	39 -47	31 – 47
Inactive Drain (low temp)		bagged: 23 - 30 %/hr; non-bagged: 0 to 7.0 %/hr			

Table 3-9. Emission Factors: $0.32 \leq Hc < 1.23$

Hc Range: $0.32 \leq Hc < 1.23$ (volatile)		% Emissions			
		Low Velocity		High Velocity	
		Bagged	Non-bagged	Bagged	Non-bagged
Low Temp	Low Height	7.0 - 15	38 - 57	9.0 - 29	21 – 32
	High Height	10 - 21	44 - 69	11 - 28	22 – 28
High Temp	Low Height	18 - 27	59 - 71	23 - 43	24 – 57
	High Height	15 - 31	58 - 59	21 - 39	31 – 39
Inactive Drain (low temp)		bagged: 8.2 - 23 %/hr; non-bagged: 0 to 2.6 %/hr			

Table 3-10. Emission Factors: $0.13 \leq Hc < 0.32$

Hc Range: $0.13 \leq Hc < 0.32$ (moderately volatile)		% Emissions			
		Low Velocity		High Velocity	
		Bagged	Non-bagged	Bagged	Non-bagged
Low Temp	Low Height	4.0 - 12	29 - 38	2.5 - 10	16 – 23
	High Height	3.0 - 10	0 - 45	3.0 - 12	14 – 22
High Temp	Low Height	12 - 19	46 - 64	9.0 - 23	13 – 27
	High Height	9.0 - 17	39 - 64	10 - 21	18 – 39
Inactive Drain (low temp)		bagged: 7.7 - 9.5 %/hr; non-bagged: 0 to 3.9 %/hr			

Table 3-11. Emission Factors: $0.02 \leq Hc < 0.13$

Hc Range: $0.02 \leq Hc < 0.13$ (semi to moderately volatile)		% Emissions			
		Low Velocity		High Velocity	
		Bagged	Non-bagged	Bagged	Non-bagged
Low Temp	Low Height	1.0 - 4.0	19 - 29	1.0 - 2.5	7.0 – 23
	High Height	1.0 - 3.0	0 - 6.4	1.0 - 3.0	8.9 – 14
High Temp	Low Height	2.0 - 12	41 - 46	2.0 - 9.0	5.0 – 13
	High Height	2.0 - 9.0	32 - 39	2.0 - 10	18 – 20
Inactive Drain (low temp)		bagged: 0.3 - 3.8 %/hr; non-bagged: 0.3 to 5.6 %/hr			

Organic Vapor Analyzer Results. The OVA was used during all of the emission factor experiments. Ambient OVA and test OVA readings during the experiments are presented in Table 3-12. Since the OVA values represent all of the compounds tested, no volatility range is required in Table 3-12. The OVA measurements for the bagged experiments were converted to total mass emission rates following the procedure outlined in the 1995 EPA Protocol (USEPA, 1995a). The bagging procedure presented in the 1995 protocol is reproduced in Appendix F and the total contaminant mass emissions calculated are presented in Table 3-13. In addition to the OVA based emission rates, Table 3-13 contains the emission rates based on the gas phase concentrations and the ratio of the OVA to gas phase emission rates. This ratio ranges from 0.46 to 1.0

When calculating the OVA mass emission rates, the contaminant mixture's collective molecular weight and response factor, were determined based on the gas phase analytical results. Although OVA measurements for the non-bagged condition were collected, the mass emission rate for the non-bagged condition can not be determined due to an unknown airflow rate sweeping past the drain.

Table 3-12. Organic Vapor Analyzer Results

		OVA (ppmV) (net increase over background)			
		Low Velocity		High Velocity	
		Bagged	Non-bagged	Bagged	Non-bagged
Low Temp	Low Height	25	3	15, 23**	1
	High Height	19	1	13	1
High Temp	Low Height	28	8*	30	3
	High Height	35	8*	46	3
Inactive Drain (low temp)		0 (bagged) ; – (non-bagged)			

*: value obtained with repeat experiment, OVA unavailable for first set of experiments
**: repeat experiment result
--: no OVA measurements taken

Table 3-13. Drain Emissions Based OVA Measurements - Bagged Experiments

		Mass Emission Rate (µg/min) and Ratio*					
		Low Velocity, Bagged			High Velocity, Bagged		
		OVA	Gas	Ratio**	OVA	Gas*	Ratio**
Low Temp	Low Height	489	513	0.95	374 385***	480 794***	0.78 0.48***
	High Height	605	676	0.89	322	698	0.46
High Temp	Low Height	686	1010	0.68	886	1220	0.73
	High Height	1010	1010	1.0	968	1080	0.90
Inactive Drain (low temp, bagged)		OVA = 0; GAS = 17.8; Ratio = 0					

*: Mass emissions based on gas phase concentrations and flowrates in bagged experiments
**: OVA mass emission rates divided by gas phase based mass emission rates; bagged experiments only
***: indicates repeat experiment conducted under these conditions

Mass emissions based on OVA screening values are also presented in the 1995 EPA Protocol (USEPA, 1995a). In this reference, correlations of mass emissions as a function of screening value are presented for a variety of petroleum equipment components (valves, pump seals, connectors etc). Figure 3-6 presents both the EPA correlation (for "other" components) and the experimental results from this work. The experimental data values range from 27% to 55% (average of 41%) of the EPA correlation. This value may be due to a combination of the compounds used and their corresponding OVA response factors, however, it does indicate that the two are in the same order of magnitude.

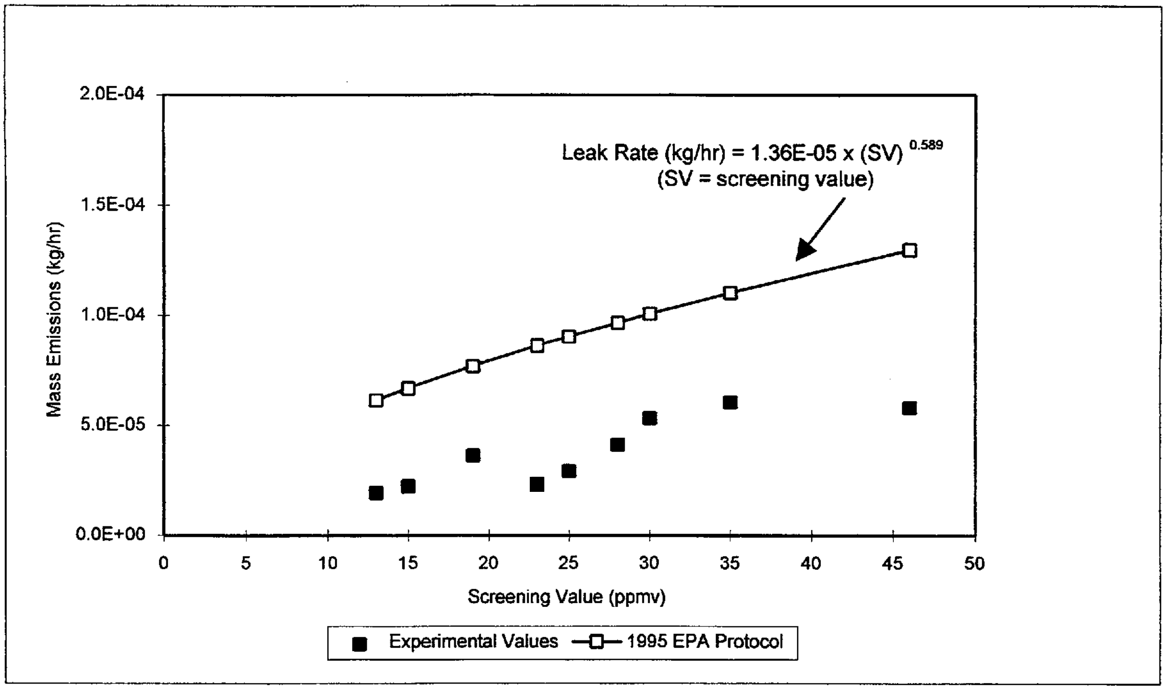

Figure 3-6. Mass Emissions as a Function of OVA Reading

Aligned Drain Structure

The analytical results for the aligned drain experiments A1 and A2 are presented in Appendix C. The percentage emissions were calculated based on the influent and effluent liquid concentrations using Equation 3-2 with the results presented in Table 3-14. In addition to the aligned experiments, the emissions for the corresponding misaligned experiments are presented. That is, experiment A1 is the aligned version of experiment 7b and A2 is the aligned version of 1b. Although there are differences between the aligned and misaligned drain experiments, there is no clear observable trend as to which reports the greater percentage emissions.

Table 3-14. Aligned Drain Percentage Emissions

	Percentage Emissions (%)			
Experiment	low temp, high velocity, high height		low temp, high velocity, low height	
	Aligned A1	Misaligned 7b	Aligned A2	Misaligned 1b
Compound				
Cyclohexane	30	33	22	32
Tetrachoromethane	21	28	39	32
Tetrachloroethylene	23	23	26	21
Ethylbenzene	18	22	14	21
Toluene	15	22	16	23
o-Xylene	11	17	12	16
1,4-Dichlorobenzene	3.1	14	14	23
Bromoform	3.7	8.9	8.2	7.0

Duplication of University of Texas Experiments

As indicated previously, five experiments were conducted on a modified version of the drain structure used for the emission factor experiments. This drain structure was intended to resemble that used at the University of Texas. Three of the five experiments repeated conditions used at the University of Texas (designated here as UT1, UT2, UT3) and two of the five examined the effect of liquid film height (designated as UT4 and UT5). The analytical results of the experiments are presented in Appendix C. The percentage emissions were based on the influent and effluent liquid concentrations (Equation 3-2) with the results as presented in Table 3-15. At the low discharge rate of 3.8 L/min (comparing experiments designated as UT1 and UT4), percentage emissions were significantly greater at the 62 cm film drop height compared to the 31 cm drop height. At the higher discharge rate of 11.4 L/min (comparing experiments designated as UT3 and UT5), percentage emissions are similar for the 31 cm and 62 cm film fall height. At the 31 cm fall height (experiments UT1, UT2, UT3), percentage emissions decrease as flow rate increases.

The three University of Texas replication experiments (designated here as UT1, UT2, UT3) were compared to the results obtained in this work. The drain emissions model developed at the University of Texas (draft model, file data May 12, 1997) were used to represent the University of Texas results since their model and experimental values were similar. For example, The University of Texas results with operating conditions similar to this work's experiment UT1 had experimental emissions of 19.9% and 18.4% for ethylbenzene and toluene, respectively and model results of 21% and 21% for ethylbenzene and toluene. In the model, compound parameters for liquid phase and gas phase diffusion coefficients were obtained from USEPA's WATER8 version 3 (USEPA, 1995b). No diffusion coefficients were available for cyclohexane in WATER8 and, therefore, modeling results are not included for this compound. Table 3-16 presents both the University of Texas model results and the similar process conditions experiments conducted in this study. In general, the percentage emissions calculated during this work was greater than that determined using the model. There is no readily apparent reason for the differences.

Table 3-15. University of Texas Experiments - Percentage Emissions

Experiment	UT1	UT2	UT3	UT4	UT5
Discharge Flow Rate [L/min]	3.8	7.6	11.4	3.8	11.4
Film Fall Height (cm)	31	31	31	62	62
Compound	Percentage Emissions (%)				
Cyclohexane	38	41	31	38	35
Tetrachoromethane	43	18	42	62	7.8
Tetrachloroethylene	31	27	21	46	16
Ethylbenzene	29	22	16	43	18
Toluene	31	25	14	37	17
o-Xylene	26	13	12	36	10
1,4-Dichlorobenzene	23	12	10	38	-48
Bromoform	14	6	5.4	26	35

Table 3-16. Study Emissions and University of Texas Model Emissions

Experiment	UT1	U of T model	UT2	U of T Model	UT3	U of T Model
Compound	Percentage Emissions (%)					
Cyclohexane	38	--	41	--	31	--
Tetrachloromethane	43	25	18	15	42	11
Tetrachloroethylene	31	23	27	12	21	8.4
Ethylbenzene	29	21	22	8.7	16	5.1
Toluene	31	21	25	7.7	14	4.4
o-Xylene	26	20	13	6.6	12	3.6
1,4-Dichlorobenzene	23	16	12	4.3	10	2.2
Bromoform	14	2.3	6	0.4	5.4	0.2

DISCUSSION OF RESULTS

Emission Factor Tables and Experiments: A number of observations can be made with respect to the four emission factor tables presented:

- Percentage emissions under bagged conditions are generally less than the non-bagged percentage emissions with the difference being more pronounced for lower volatile compounds.

As part of the Phase 2 study, a statistical difference was found between the percentage emissions observed for the bagged and non-bagged techniques for all except the most volatile compound. This was also observed during this work, although it should be noted that statistical analyses can not be used on these data due to its limited duplication of individual experiments.

It should be noted that in many of the bagged experiments contaminant concentrations in the gas phase were near saturation levels. The degree of saturation is the contaminant concentration in the gas phase divided by the gas phase concentration if it were in equilibrium with the liquid concentration in the p-trap. The degree of saturation, expressed as a percentage, for each of the bagged experiments is presented in Appendix E. Cyclohexane consistently had degrees of saturation 15% or less, while the other contaminants had concentrations consistently greater than 30% and often greater than 70% of saturation.

- High velocity discharges generally had lower percentage emissions than low velocity conditions for the non-bagged condition. For bagged conditions, there was no apparent difference in percentage emissions between the high and low velocity discharges.

- When developing the emission factor tables, there was no evidence to suggest that the height of the drop of the discharge stream above the plane of the hub has an effect on percentage emissions (4 and 9 inch heights).

  Replication of the University of Texas experiments indicated that the liquid film fall height (distance from discharge to water surface with the exposed liquid film height constant) impacts the percentage emissions. It is possible that at the greater liquid film heights used in the emission factor tables, the small relative difference in film fall height (5 inches or 15% of film fall height of 34 inches) does not significantly impact emissions.

- The data suggest that low temperature (20 °C) discharge water results in lower percentage emissions than high temperature (40 °C) discharge water.

SIMPLIFIED EMISSION FACTOR TABLES

As part of the pilot scale determination of drain stripping efficiencies project, emission factor tables were generated which, as a function of drain operating condition, indicated the fraction of the influent contaminant mass flow to the drain that would be emitted to the air. In an attempt to make these tables easier to use for operational staff, they have been simplified. This section outlines what assumptions have been made when modifying the tables and how to use the modified tables (including an example).

Summary tables were created for the misaligned drain experiments. Three tables were created representing high, medium and low volatility as opposed to the four presented earlier. In creating the summary tables, the following assumptions were made:

- All emissions are based on non-bagged experiments.

  The bagged experiments had lower emissions than the non-bagged experiments. These suppressed emission conditions would not likely represent actual operating conditions and were, therefore, not included.

- Emission summary table cells values represent the midpoint value of a range.

  Since each of the summary tables represent a range of volatilities, there will be a range of emissions associated with each operating condition. To reduce the complexity of the system, a single value was selected to represent each operating condition's range of emissions. The range midpoint was used for this purpose.

- Inactive drain trap volume is 6.8L.

- Operating conditions outlined in the summary tables represent typical process drain conditions

  The operating conditions for the emissions summary tables are presented in Table 3-17.

Table 3-17. Simplified Emission Factor Table Summary of Drain Operating Conditions

Condition	Value
Discharge Temperature [°C]	
Low	20
High	40
Discharge Velocity [L/(cm^2 min)]*	
Low	0.39
High	1.56
Wastewater Discharge Height Above Hub of Drain (inches)	
Low	4
High	9
Wastewater Discharge Alignment With Drain	
Misaligned	Discharge onto sloped funnel portion

*:Values based on wastewater flowrate (2 and 8 L/min) divided by nominal cross sectional area of discharge pipe (dia. nominal = 1", cross-sectional surface area approximately 5.1 cm^2)

- Two discharge flow operating regions (≤ 0.67 gpm/inch^2 and > 0.67 gpm/inch^2) were created based on the two experimental discharge flow operating conditions (0.67 gpm/inch^2 and 2.7 gpm/inch^2). The selection of the two regions were based on conservative emissions considerations.

- Two temperature regions (≤ 20°C and > 20°C) were created based on the experimental temperature conditions (20°C and 40°C). The selection of the two regions were based on conservative emissions considerations.

- Two discharge height regions (≤ 4 inches and > 4 inches) were created based on the experimental discharge height conditions (4 inches and 9 inches). The selection of the two regions were based on conservative emissions considerations.

- The experimental inactive drain temperature of approximately 20°C is representative of all temperatures.

Examples of Compounds in each volatility range are presented in below in Table 3-18 to Table 3-20.

Table 3-18. High Volatility Compounds ($1.23 \leq Hc \leq 7.17$)

Cyclohexane	Carbon tetrachloride (tetrachloromethane)
Propylene	Vinyl chloride (chloroethane)
1,3-butadiene	Carbon disulfide
Dicyclopentadiene	2-methylpentane

Table 3-19. Medium Volatility Compounds ($0.13 \leq Hc < 0.32$)

Tetrachloroethylene	Hexachloroethane
Chloroethane (ethyl chloride)	Benzene
Cumene (isopropylbenzene)	Toluene
Propyl benzene	Ethylbenzene
Nonane	Xylenes
Methyl chloride (chloromethane)	Chloroform

Table 3-20. Low Volatility Compounds ($\leq 0.02\ Hc < 0.13$)

Dichlorobenzene (m,o,p)	1,2-dichloroethane (ethylene dichloride)
Styrene	Ethyl ether
Diisopropylether	Bromoform
Hexachlorobenzene	Vinyl acetate

The simplified emission factors for the three volatility ranges are presented in Table 3-21 to Table 3-23.

Table 3-21. Simplified Emission Factor Table - High Volatility

$0.72 \leq Hc \leq 7.17$		Mass Emissions [(lb/hr)/(ppm_w gpm)]	
		Low Velocity (≤ 0.67 gpm/inch^2)	High Velocity (> 0.67 gpm/inch^2)
Low Temp (≤ 20°C)	Low Height (≤ 4")	0.258×10^{-3}	0.130×10^{-3}
	High Height (>4")	0.298×10^{-3}	0.139×10^{-3}
High Temp (>20°C)	Low Height (≤ 4")	0.340×10^{-3}	0.215×10^{-3}
	High Height (>4")	0.309×10^{-3}	0.194×10^{-3}
Inactive Drain		5.29×10^{-7} [(lb/hr)/(ppm_w)]	

Table 3-22. Simplified Emission Factor Table - Medium Volatility

$0.13 \leq Hc < 0.72$		Mass Emissions [(lb/hr)/(ppm_w gpm)]	
		Low Velocity (≤ 0.67 gpm/inch^2)	High Velocity (> 0.67 gpm/inch^2)
Low Temp (≤ 20°C)	Low Height (≤4")	0.189×10^{-3}	0.110×10^{-3}
	High Height (>4")	0.170×10^{-3}	0.0896×10^{-3}
High Temp (>20°C)	Low Height (≤4")	0.279×10^{-3}	0.105×10^{-3}
	High Height (>4")	0.258×10^{-3}	0.139×10^{-3}
Inactive Drain		3.08×10^{-7} [(lb/hr)/(ppm_w)]	

Table 3-23. Simplified Emission Factor Table - Low Volatility

$0.02 \leq Hc < 0.13$		Mass Emissions [(lb/hr)/(ppm_w gpm)]	
		Low Velocity (≤ 0.67 gpm/inch^2)	High Velocity (> 0.67 gpm/inch^2)
Low Temp (≤ 20°C)	Low Height (≤ 4")	0.119×10^{-3}	0.0745×10^{-3}
	High Height (>4")	0.0158×10^{-3}	0.0783×10^{-3}
High Temp (>20°C)	Low Height (≤ 4")	0.219×10^{-3}	0.0448×10^{-3}
	High Height (>4")	0.179×10^{-3}	0.0943×10^{-3}
Inactive Drain		4.40×10^{-7} [(lb/hr)/(ppm_w)]	

Using the Simplifed Emission Factor Tables

A brief outline of how to use the emission tables is presented followed by an example.

The emission factor tables can be used for both active drains and inactive drains or for drains that are both active and inactive. To use the emission factor summary tables, the following steps are followed:

- The following information is required in order to use the emission factor tables:

Pipe discharge flow	(gpm)
Pipe diameter	(inches)
Discharge height	(inches)
Period of day drain is active	(hrs/day)
Total estimated influent concentrations for each volatile category	(mg/L)

Active Drains:

- Determine the actual operating conditions of the drain and select from each summary table the operating conditions which most closely resemble the actual operating conditions. Record the active drain emission factors (EF) from the table for each volatility category.

- For each volatility range, determine the active drain mass emissions (Ma) by multiplying the emission factor (EF) by the influent discharge concentration (C) and the flow rate (Q).
  ($Ma = EF \times C \times Q$).

- Sum the mass emissions for the three volatility ranges.
  ($Ma_{total} = Ma_{high\ volatility} + Ma_{medium\ volatility} + Ma_{low\ volatility}$) (lb/hr)

- Multiply the mass emissions for the active drain (lb/hr) by the number of hours per day the drain is active. This is the daily mass emissions from the active drain.

Inactive Drains:

- For each volatility range, record the emission factor (EF) for the inactive drain.

- For each volatility range, determine the inactive drain emissions (Mi) by multiplying the emission factor (EF) by the discharge concentration assumed for the active drain (C).
  (Mi = EF x C)

- Sum the mass emissions for the three volatility ranges.
  $(Mi_{total} = Mi_{high\ volatility} + Mi_{medium\ volatility} + Mi_{low\ volatility})$ (lb/hr)

- Multiply the mass emissions for the inactive drain (lb/hr) by the number of hours per day the drain is inactive (24 minus active time of drain). This is the daily mass emissions from the active drain.

Total of Inactive and Active Drain Emissions:

- Sum the active and inactive drain emissions.

Example Use of the Emission Factor Tables. An example of how to use the emission factor tables is presented in this section. The example is in a form that can easily be adapted to a spreadsheet format. Required user input data are indicated by the numbers in bold type.

User Input Data

Pipe Data

Q =	**5**	gpm	flow through pipe
dia =	**4**	inches	pipe diameter
discharge height =	**2**	inches	height of discharge above plane of drain hub
Active time =	**8**	hrs/day	time during day the drain is active

Discharge Data

Temp =	**19**	deg C	discharge temperature
C(high) =	**5**	mg/L (ppm_w)	total high volatilty range concentration
C(medium) =	**20**	mg/L (ppm_w)	total medium vol. range concentration
C(low) =	**6**	mg/L (ppm_w	total low volatility range concentration

User Input: Look-up Table Mass Emissions

based on:

Temp =	**19**	deg C	discharge temperature
Discharge height =	**2**	inches	height of discharge above plane of drain hub
Flow Velocity =	**0.40**	gal/(min in^2)	calculated flow velocity through pipe

use:
low temperature
low discharge height
low flow velocity

values input by user:

C(high table) =	**0.258×10^{-3}**	[(lb/hr)/(ppm_w gpm)	high volatility value
C(medium table) =	**0.189×10^{-3}**	[(lb/hr)/(ppm_w gpm)	medium volatility value
C(low table) =	**0.119×10^{-3}**	[(lb/hr)/(ppm_w gpm)	low volatility value

Calculations

Active Drain Emissions

$$Ma = (EF) \times (C) \times (Q)$$

where:

Ma = mass emissions from active drain [lb/hr]
EF = emission factor from table [(lb/hr)/(ppm$_w$ gpm)]
C = discharge concentration [mg/L or ppm$_w$]
Q = discharge flow rate [gpm]

	Volatility Range			
	High	Medium	Low	Total
EF [(lb/hr)/(ppm$_w$ gpm)]	0.258×10^{-3}	0.189×10^{-3}	0.119×10^{-3}	
C [mg/L or ppm$_w$]	5	20	6	
Q [gpm]	5	5	5	
Ma (EF x C x Q) [lb/hr]	6.45×10^{-3}	18.9×10^{-3}	3.57×10^{-3}	**28.9×10^{-3}**

The estimated active drain emissions are 28.9×10^{-3} lb/hr.

Inactive Drain Emissions

$$Mi = (EF) \times (C)$$

where:

Mi = mass emissions from inactive drain [lb/hr]
EF = emission factor from table [(lb/hr)/(ppm$_w$)]
C = discharge concentration [mg/L or ppm$_w$]

	Volatility Range			
	High	Medium	Low	Total
EF [(lb/hr)/(ppm$_w$)]	5.29×10^{-7}	3.08×10^{-7}	4.40×10^{-7}	
C [mg/L or ppm$_w$]	5	20	6	
Mi (EF x C) [lb/hr]	2.64×10^{-6}	6.16×10^{-6}	2.64×10^{-6}	**11.4×10^{-6}**

The estimated inactive drain emissions are 11.4×10^{-6} lb/hr.

Total Daily Emissions

$M = (Ma \times ta) + (Mi \times ti)$

where:

M	= total daily mass emissions (active plus inactive)	[lb/d]
ta	= number of hours per day drain is active	[hr/d]
ti	= number of hours per day drain is inactive	[hr/d]

	Volatility Range		
	M [lb/hr]	t [hr/d]	Total [lb/d]
Active Drain	28.9×10^{-3}	8	231×10^{-3}
Inactive Drain	11.4×10^{-6}	16	0.182×10^{-3}
Total (active + inactive)			**0.231**

The estimated total drain emissions are 0.231 lb/d.

4. CONCLUSIONS AND RECOMMENDATIONS

The AP-42 emission factor for refinery process drains is 0.07 pounds VOCs per hour per drain. This factor can be compared with a conservative emission factor derived from the emission factor tables presented here. Table 4-1 develops an emission factor based on the highest values encountered during the pilot scale studies. These results indicate that the AP-42 emission factor for refinery process drains generally overestimates emissions from these drains and should be modified.

Table 4-1. Conservative Use of Emission Factor Tables

Compound	Simplified Emission Factor[a] (lb/hr)/(ppm$_w$ gpm)	Concentration[b] (ppm$_w$)	Discharge Flow Rate[c] (gpm)	Emission Factor (lb/hr)
Cyclohexane	0.340×10^{-3}	0.244	3.0	2.49×10^{-4}
Tetrachloromethane	0.340×10^{-3}	0.188	3.0	1.92×10^{-4}
Tetrachloroethylene	0.279×10^{-3}	0.200	3.0	1.67×10^{-4}
Toluene	0.279×10^{-3}	0.134	3.0	1.12×10^{-4}
Ethylbenzene	0.279×10^{-3}	0.172	3.0	1.44×10^{-4}
o-Xylene	0.279×10^{-3}	0.176	3.0	1.47×10^{-4}
1,4-Dichlorobenzene	0.219×10^{-3}	0.219	3.0	1.44×10^{-4}
Bromoform	0.219×10^{-3}	0.190	3.0	1.25×10^{-4}
TOTAL				1.28×10^{-3} (0.0013)

a Highest values from Tables 3-21, 3-22, or 3-23, as appropriate for compound volatility.
b Highest value from Appendices A, B, or C, for each compound for active and inactive drain experiments.
c Highest value during study (11.4 L/min).

These conservative values lead to a refinery drain emission factor of 0.001 pounds VOCs per hour per drain.

5. REFERENCES

American Petroleum Institute. 1996. *Phase 1 report: Estimation of fugitive emissions from petroleum refinery process drains.* API Publication No. 4639.

USEPA. 1995a. *1995 Protocol for equipment leak emission estimates.* EPA-453/R-95-017.

USEPA. 1995b. WATER8. Predictive fate model for wastewater. Version 3.0, February 1995.

APPENDIX A

Analytical Data
From Drain Bagging Protocol Experiments

Table A-1. Analytical Data - Experiment 1 (no bag)						
Compound	Influent (µg/L)			Effluent (µg/L)		
	Sample 1	Sample 2	Sample 3	Sample 1	Sample 2	Sample 3
Cyclohexane	5.16	5.18	5.39	3.08	2.83	—
Tetrachloroethylene	36.5	34.5	34.2	23.1	21.2	—
1,1,1-Trichloroethane (methyl chloroform)	41.8	39.9	42.8	25.8	29.4	—
Ethylbenzene	47.3	52.5	45.2	31.5	31.3	—
Toluene	60.8	54.4	52.1	38.6	37.7	—
o-Xylene	40.3	39.9	39.5	27.5	28.8	—

Table A-2. Analytical Data - Experiment 2 (vacuum)						
Compound	Influent (µg/L)			Effluent (µg/L)		
	Sample 1	Sample 2	Sample 3	Sample 1	Sample 2	Sample 3
Cyclohexane	5.05	4.73	—	2.83	—	—
Tetrachloroethylene	37.2	36.6	—	26.2	—	—
1,1,1-Trichloroethane (methyl chloroform)	36.3	36.2	—	26.2	—	—
Ethylbenzene	37.5	37.2	—	29.7	—	—
Toluene	57	56.2	—	45.7	—	—
o-Xylene	43.0	43.0	—	35.7	—	—

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Table A-3. Analytical Data - Experiment 3 (blow-through)

Compound	Influent (µg/L)			Effluent (µg/L)		
	Sample 1	Sample 2	Sample 3	Sample 1	Sample 2	Sample 3
Cyclohexane	5.67	—	—	4.10	3.65	—
Tetrachloroethylene	44.4	—	—	—	—	—
1,1,1-Trichloroethane (methyl chloroform)	39.8	—	—	32.5	29.9	—
Ethylbenzene	40.6	—	—	36.0	33.7	—
Toluene	59.2	—	—	53.3	46.0	—
o-Xylene	51.5	—	—	47.2	44.5	—

Table A-4. Analytical Data – Experiment 4 (vacuum)

Compound	Influent (µg/L)			Effluent (µg/L)		
	Sample 1	Sample 2	Sample 3	Sample 1	Sample 2	Sample 3
Cyclohexane	15.3	—	—	9.84	—	—
Tetrachloroethylene	54.1	—	—	39.4	—	—
1,1,1-Trichloroethane (methyl chloroform)	66.6	—	—	45.2	—	—
Ethylbenzene	37.6	—	—	31.2	—	—
Toluene	65.0	—	—	57.7	—	—
o-Xylene	62.0	—	—	53.2	—	—

Table A-5. Analytical Data – Experiment 5 (no bag)

Compound	Influent (µg/L)			Effluent (µg/L)		
	Sample 1	Sample 2	Sample 3	Sample 1	Sample 2	Sample 3
Cyclohexane	14.0	—	—	9.15	9.11	—
Tetrachloroethylene	53.2	—	—	37.6	35.6	—
1,1,1-Trichloroethane (methyl chloroform)	61.2	—	—	42.1	43.4	—
Ethylbenzene	36.7	—	—	28.7	29	—
Toluene	68.6	—	—	55.0	53.5	—
o-Xylene	59.9	—	—	50.0	51.0	—

Table A-6. Analytical Data - Experiment 6 (no bag)

Compound	Influent (µg/L)			Effluent (µg/L)		
	Sample 1	Sample 2	Sample 3	Sample 1	Sample 2	Sample 3
Cyclohexane	13.2	—	—	8.31	—	—
Tetrachloroethylene	53.1	—	—	35.1	—	—
1,1,1-Trichloroethane (methyl chloroform)	60.2	—	—	39.0	—	—
Ethylbenzene	44.7	—	—	31.4	—	—
Toluene	64.0	—	—	49.6	—	—
o-Xylene	59.2	—	—	47.2	—	—

Table A-7. Analytical Data - Experiment 7 (blow-through)

Compound	Influent (µg/L)			Effluent (µg/L)		
	Sample 1	Sample 2	Sample 3	Sample 1	Sample 2	Sample 3
Cyclohexane	14.1	17.5	—	9.31	10.1	—
Tetrachloroethylene	49.8	55.5	—	39.8	37.8	—
1,1,1-Trichloroethane (methyl chloroform)	61.2	62.4	—	49.4	53.8	—
Ethylbenzene	42.6	41.5	—	38.2	35.6	—
Toluene	60.8	59.2	—	56.3	49.9	—
o-Xylene	59.4	57.8	—	54.4	51.8	—

Table A-8. Analytical Data - Experiment 8 (blow-through)

Compound	Influent (µg/L)			Effluent (µg/L)		
	Sample 1	Sample 2	Sample 3	Sample 1	Sample 2	Sample 3
Cyclohexane	17.4	—	—	10.8	—	—
Tetrachloroethylene	56.8	—	—	42.7	—	—
1,1,1-Trichloroethane (methyl chloroform)	77.0	—	—	54.3	—	—
Ethylbenzene	62.0	—	—	51.6	—	—
Toluene	80.0	—	—	70.1	—	—
o-Xylene	68.7	—	—	58.3	—	—

Table A-9. Analytical Data - Experiment 9 (no bag)						
Compound	Influent (µg/L)			Effluent (µg/L)		
	Sample 1	Sample 2	Sample 3	Sample 1	Sample 2	Sample 3
Cyclohexane	17.4	—	—	10.5	—	—
Tetrachloroethylene	54.9	—	—	37.1	—	—
1,1,1-Trichloroethane (methyl chloroform)	71.1	—	—	45.8	—	—
Ethylbenzene	47.2	—	—	36.0	—	—
Toluene	72.4	—	—	60.9	—	—
o-Xylene	62.5	—	—	51.5	—	—

Table A-10. Analytical Data - Experiment 10 (blow-through)						
Compound	Influent (µg/L)			Effluent (µg/L)		
	Sample 1	Sample 2	Sample 3	Sample 1	Sample 2	Sample 3
Cyclohexane	16.0	16.9	—	10.4	—	—
Tetrachloroethylene	53.5	48.6	—	38.7	—	—
1,1,1-Trichloroethane (methyl chloroform)	69.0	62.4	—	45.2	—	—
Ethylbenzene	47.3	56.0	—	39.5	—	—
Toluene	83.3	72.3	—	64.6	—	—
o-Xylene	63.7	61.6	—	55.9	—	—

Table A-11. Analytical Data - Experiment 11 (vacuum)

Compound	Influent (µg/L)			Effluent (g/L)		
	Sample 1	Sample 2	Sample 3	Sample 1	Sample 2	Sample 3
Cyclohexane	19.8	24.1	—	11.1	11.1	13.8
Tetrachloroethylene	53.9	55.0	—	40.8	38.0	40.8
1,1,1-Trichloroethane (methyl chloroform)	77.4	71.4	—	46.0	47.7	55.5
Ethylbenzene	56.4	53.8	—	46.4	45.7	47.0
Toluene	76.7	67.2	—	69.2	58.6	59.2
o-Xylene	62.6	60.5	—	55.1	54.7	55.4

Table A-12. Analytical Data - Experiment 12 (vacuum)

Compound	Influent (µg/L)			Effluent (µg/L)		
	Sample 1	Sample 2	Sample 3	Sample 1	Sample 2	Sample 3
Cyclohexane	20.6	—	—	12.4	—	—
Tetrachloroethylene	54.9	—	—	41.2	—	—
1,1,1-Trichloroethane (methyl chloroform)	69.2	—	—	54.1	—	—
Ethylbenzene	46.7	—	—	39.6	—	—
Toluene	79.0	—	—	66.2	—	—
o-Xylene	63.5	—	—	55.1	—	—

Appendix B

QA/QC - Duplicate Sample Submission From Drain Bagging Protocol Experiments

Table B-1. Analytical Data - Experiment 1 (no bag)

Compound	Influent			Effluent (µg/L)		
	# samples	Avg (µg/L)	COV (%)	# samples	Avg (µg/L)	COV(%)
Cyclohexane	3	5.24	2.4	2	2.96	6.0
Tetrachloroethylene	3	35.1	3.6	2	22.2	6.1
1,1,1-Trichloroethane (methyl chloroform)	3	41.5	3.5	2	27.6	9.2
Ethylbenzene	3	48.3	7.8	2	31.4	0.5
Toluene	3	55.8	8.1	2	38.2	1.7
o-Xylene	3	39.9	1.0	2	28.2	3.3

Table B-2. Analytical Data - Experiment 2 (vacuum)

Compound	Influent			Effluent (µg/L)		
	# samples	Avg (µg/L)	COV (%)	# samples	Avg (µg/L)	COV(%)
Cyclohexane	2	4.89	4.6	1	2.83	—
Tetrachloroethylene	2	36.9	1.1	1	26.2	—
1,1,1-Trichloroethane (methyl chloroform)	2	36.3	0.2	1	26.2	—
Ethylbenzene	2	37.4	0.6	1	29.7	—
Toluene	2	0.57	1.0	1	45.7	—
o-Xylene	2	43.0	0	1	35.7	—

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Table B-3. Analytical Data - Experiment 3 (blow-through)						
Compound	Influent			Effluent (µg/L)		
	# samples	Avg (µg/L)	COV (%)	# samples	Avg (µg/L)	COV(%)
Cyclohexane	1	5.67	—	2	3.88	8.2
Tetrachloroethylene	1	44.4	—	2	33.6	8.8
1,1,1-Trichloroethane (methyl chloroform)	1	39.8	—	2	31.2	5.9
Ethylbenzene	1	40.6	—	2	34.9	4.7
Toluene	1	59.2	—	2	49.7	10.4
o-Xylene	1	51.5	—	2	45.9	4.2

Table B-4. Analytical Data - Experiment 4 (vacuum)						
Compound	Influent			Effluent (µg/L)		
	# samples	Avg (µg/L)	COV (%)	# samples	Avg (µg/L)	COV(%)
Cyclohexane	1	15.3	—	1	9.84	—
Tetrachloroethylene	1	54.1	—	1	39.4	—
1,1,1-Trichloroethane (methyl chloroform)	1	66.6	—	1	45.2	—
Ethylbenzene	1	37.6	—	1	31.2	—
Toluene	1	65.0	—	1	57.7	—
o-Xylene	1	62.0	—	1	53.2	—

Table B-5. Analytical Data - Experiment 5 (no bag)

Compound	Influent			Effluent (µg/L)		
	# samples	Avg (µg/L)	COV (%)	# samples	Avg (µg/L)	COV(%)
Cyclohexane	1	14.0	—	2	9.18	0.3
Tetrachloroethylene	1	53.2	—	2	36.6	3.9
1,1,1-Trichloroethane (methyl chloroform)	1	61.2	—	2	42.8	2.2
Ethylbenzene	1	36.7	—	2	28.9	0.7
Toluene	1	68.6	—	2	54.3	2.0
o-Xylene	1	59.9	—	2	50.5	1.4

Table B-6. Analytical Data - Experiment 6 (no bag)

Compound	Influent			Effluent (µg/L)		
	# samples	Avg (µg/L)	COV (%)	# samples	Avg (µg/L)	COV(%)
Cyclohexane	1	13.2	—	1	8.31	—
Tetrachloroethylene	1	53.1	—	1	35.1	—
1,1,1-Trichloroethane (methyl chloroform)	1	60.2	—	1	39.0	—
Ethylbenzene	1	44.7	—	1	31.4	—
Toluene	1	64.0	—	1	49.6	—
o-Xylene	1	59.2	—	1	47.2	—

Table B-7. Analytical Data - Experiment 7 (pressure)

Compound	Influent			Effluent (µg/L)		
	# samples	Avg (µg/L)	COV (%)	# samples	Avg (µg/L)	COV(%)
Cyclohexane	2	15.8	15.2	2	9.71	5.8
Tetrachloroethylene	2	52.7	7.7	2	38.8	3.6
1,1,1-Trichloroethane (methyl chloroform)	2	61.8	1.4	2	51.6	6.0
Ethylbenzene	2	42.1	1.8	2	36.9	5.0
Toluene	2	60.0	1.9	2	53.1	8.5
o-Xylene	2	58.6	1.9	2	53.1	3.5

Table B-8. Analytical Data - Experiment 8 (pressure)

Compound	Influent			Effluent (µg/L)		
	# samples	Avg (µg/L)	COV (%)	# samples	Avg (µg/L)	COV(%)
Cyclohexane	1	17.4	—	1	10.8	—
Tetrachloroethylene	1	56.8	—	1	42.7	—
1,1,1-Trichloroethane (methyl chloroform)	1	77.0	—	1	54.3	—
Ethylbenzene	1	62.0	—	1	51.6	—
Toluene	1	80.0	—	1	70.1	—
o-Xylene	1	68.7	—	1	58.3	—

Table B-9. Analytical Data - Experiment 9 (no bag)

Compound	Influent			Effluent (µg/L)		
	# samples	Avg (µg/L)	COV (%)	# samples	Avg (µg/L)	COV(%)
Cyclohexane	1	17.4	—	1	10.5	—
Tetrachloroethylene	1	54.9	—	1	37.1	—
1,1,1-Trichloroethane (methyl chloroform)	1	71.1	—	1	45.8	—
Ethylbenzene	1	47.2	—	1	36.0	—
Toluene	1	72.4	—	1	60.9	—
o-Xylene	1	62.5	—	1	51.5	—

Table B-10. Analytical Data - Experiment 10 (pressure)

Compound	Influent			Effluent (µg/L)		
	# samples	Avg (µg/L)	COV (%)	# samples	Avg (µg/L)	COV(%)
Cyclohexane	2	16.4	3.9	1	10.4	—
Tetrachloroethylene	2	51.1	6.8	1	38.7	—
1,1,1-Trichloroethane (methyl chloroform)	2	65.7	7.1	1	45.2	—
Ethylbenzene	2	51.7	11.9	1	39.5	—
Toluene	2	77.8	10.0	1	64.6	—
o-Xylene	2	62.7	2.4	1	55.9	—

Table B-11. Analytical Data - Experiment 11 (vacuum)						
Compound	Influent			Effluent (µg/L)		
	# samples	Avg (µg/L)	COV (%)	# samples	Avg (µg/L)	COV(%)
Cyclohexane	2	22.0	13.9	3	12.0	13.0
Tetrachloroethylene	2	54.5	1.4	3	39.9	4.1
1,1,1-Trichloroethane (methyl chloroform)	2	74.4	5.7	3	49.6	9.9
Ethylbenzene	2	55.1	3.3	3	47.0	3.5
Toluene	2	72.0	9.3	3	62.3	9.6
o-Xylene	2	61.6	2.4	3	55.4	1.7

Table B-12. Analytical Data - Experiment 12 (vacuum)						
Compound	Influent			Effluent (µg/L)		
	# samples	Avg (µg/L)	COV (%)	# samples	Avg (µg/L)	COV(%)
Cyclohexane	1	20.6	—	1	12.4	—
Tetrachloroethylene	1	54.9	—	1	41.2	—
1,1,1-Trichloroethane (methyl chloroform)	1	69.2	—	1	54.1	—
Ethylbenzene	1	46.7	—	1	39.6	—
Toluene	1	79.0	—	1	66.2	—
o-Xylene	1	63.5	—	1	55.1	—

Appendix C

Analytical Data
From Stripping Efficiency Experiments

LIQUID SAMPLES

Table C-1: Analytical Data - Experiment 1a (bagged, low temperature, high velocity, low height)

Compound	Influent (µg/L or 10^{+3} ppm)			Effluent (µg/L or 10^{+3} ppm)		
	Sample 1	Sample 2	Average	Sample 1	Sample 2	Average
Cyclohexane	30.8	—	—	26.7	—	—
Tetrachloromethane	86.3	—	—	95.5	—	—
Tetrachloroethylene	62.9	—	—	51.5	—	—
Ethylbenzene	47.0	—	—	48.4	—	—
Toluene	65.0	—	—	59.2	—	—
o-Xylene	59.3	—	—	56.3	—	—
1,4-Dichlorobenzene	52.4	—	—	85.6	—	—
Bromoform	96.9	—	—	114	—	—

Table C-2: Analytical Data - Experiment 1b (non-bagged, low temperature, high velocity, low height)

Compound	Influent (µg/L or 10^{+3} ppm)			Effluent (µg/L or 10^{+3} ppm)		
	Sample 1	Sample 2	Average	Sample 1	Sample 2	Average
Cyclohexane	34.7	—	—	23.5	—	—
Tetrachloromethane	103	—	—	70.1	—	—
Tetrachloroethylene	63.5	—	—	49.9	—	—
Ethylbenzene	50.4	—	—	40.0	—	—
Toluene	65.3	—	—	50.6	—	—
o-Xylene	58.8	—	—	49.6	—	—
1,4-Dichlorobenzene	57.9	—	—	44.4	—	—
Bromoform	104	—	—	97.0	—	—

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Liquid Samples, Continued

Table C-3: Analytical Data - Experiment 2a (bagged, low temperature, low velocity, high height)

Compound	Influent (µg/L or 10^{+3} ppm)			Effluent (µg/L or 10^{+3} ppm)		
	Sample 1	Sample 2	Average	Sample 1	Sample 2	Average
Cyclohexane	46.9	—	—	19.0	—	—
Tetrachloromethane	155	—	—	88.5	—	—
Tetrachloroethylene	167	—	—	72.4	—	—
Ethylbenzene	62.6	—	—	49.4	—	—
Toluene	83.2	—	—	63.8	—	—
o-Xylene	80.6	—	—	66.5	—	—
1,4-Dichlorobenzene	146	—	—	136	—	—
Bromoform	183	—	—	179	—	—

Table C-4: Analytical Data - Experiment 2b (non-bagged, low temperature, low velocity, high height)

Compound	Influent (µg/L or 10^{+3} ppm)			Effluent (µg/L or 10^{+3} ppm)		
	Sample 1	Sample 2	Average	Sample 1	Sample 2	Average
Cyclohexane	42.4	—	—	18.5	—	—
Tetrachloromethane	146	—	—	71.5	—	—
Tetrachloroethylene	181	—	—	55.7	—	—
Ethylbenzene	63.1	—	—	35.3	—	—
Toluene	79.9	—	—	43.7	—	—
o-Xylene	81.6	—	—	47.8	—	—
1,4-Dichlorobenzene	99.5	—	—	104	—	—
Bromoform	171	—	—	160	—	—

Liquid Samples, Continued

Table C-5: Analytical Data - Experiment 3a (bagged, high temperature, low velocity, high height)

Compound	Influent (µg/L or 10^{+3} ppm)			Effluent (µg/L or 10^{+3} ppm)		
	Sample 1	Sample 2	Average	Sample 1	Sample 2	Average
Cyclohexane	26.0	—	—	16.8	—	—
Tetrachloromethane	128	—	—	68.9	—	—
Tetrachloroethylene	115	—	—	54.9	—	—
Ethylbenzene	90.9	—	—	46.7	—	—
Toluene	92.3	—	—	52.2	—	—
o-Xylene	94.3	—	—	53.1	—	—
1,4-Dichlorobenzene	103	—	—	74.3	—	—
Bromoform	148	—	—	126	—	—

Table C-6: Analytical Data - Experiment 3b (non-bagged, high temperature, low velocity, high height)

Compound	Influent (µg/L or 10^{+3} ppm)			Effluent (µg/L or 10^{+3} ppm)		
	Sample 1	Sample 2	Average	Sample 1	Sample 2	Average
Cyclohexane	45.8	—	—	20.4	20.9	20.7
Tetrachloromethane	106	—	—	51.1	64.0	57.6
Tetrachloroethylene	119	—	—	52.3	57.4	54.9
Ethylbenzene	75.2	—	—	40.5	37.8	39.2
Toluene	93.5	—	—	41.0	35.2	38.1
o-Xylene	80.0	—	—	43.5	39.9	41.7
1,4-Dichlorobenzene	141	—	—	95.0	78.5	86.8
Bromoform	129	—	—	91.9	102	97.0

Liquid Samples, Continued

Table C-7: Analytical Data - Experiment 4a (bagged, high temperature, high velocity, low height)						
Compound	Influent (µg/L or 10^{+3} ppm)			Effluent (µg/L or 10^{+3} ppm)		
	Sample 1	Sample 2	Average	Sample 1	Sample 2	Average
Cyclohexane	29.8	—	—	18.9	17.0	18.0
Tetrachloromethane	118	—	—	68.1	71.7	69.9
Tetrachloroethylene	102	—	—	72.4	70.0	71.2
Ethylbenzene	51.6	—	—	43.9	39.5	41.7
Toluene	69.0	—	—	58.6	53.5	56.1
o-Xylene	67.7	—	—	58.4	55.5	57.0
1,4-Dichlorobenzene	74.7	—	—	67.0	74.6	70.8
Bromoform	109	—	—	106	117	112

Table C-8: Analytical Data - Experiment 4b (non-bagged, high temperature, high velocity, low height)						
Compound	Influent (µg/L or 10^{+3} ppm)			Effluent (µg/L or 10^{+3} ppm)		
	Sample 1	Sample 2	Average	Sample 1	Sample 2	Average
Cyclohexane	31.2	—	—	20.4	—	—
Tetrachloromethane	155	—	—	66.0	—	—
Tetrachloroethylene	103	—	—	72.8	—	—
Ethylbenzene	54.5	—	—	41.5	—	—
Toluene	62.2	—	—	45.5	—	—
o-Xylene	66.6	—	—	55.4	—	—
1,4-Dichlorobenzene	71.5	—	—	62.4	—	—
Bromoform	106	—	—	101	—	—

Liquid Samples, Continued

Table C-9: Analytical Data - Experiment 5a (bagged, high temperature, low velocity, low height)

Compound	Influent (µg/L or 10^{+3} ppm)			Effluent (µg/L or 10^{+3} ppm)		
	Sample 1	Sample 2	Average	Sample 1	Sample 2	Average
Cyclohexane	66.7	—	—	24.1	—	—
Tetrachloromethane	138	—	—	34.0	—	—
Tetrachloroethylene	100	—	—	49.1	—	—
Ethylbenzene	66.0	—	—	42.8	—	—
Toluene	68.4	—	—	45.5	—	—
o-Xylene	87.2	—	—	58.9	—	—
1,4-Dichlorobenzene	95.2	—	—	85.9	—	—
Bromoform	107	—	—	85.3	—	—

Table C-10: Analytical Data - Experiment 5b (non-bagged, high temperature, low velocity, low height)

Compound	Influent (µg/L or 10^{+3} ppm)			Effluent (µg/L or 10^{+3} ppm)		
	Sample 1	Sample 2	Average	Sample 1	Sample 2	Average
Cyclohexane	64.4	—	—	32.0	—	—
Tetrachloromethane	147	—	—	54.4	—	—
Tetrachloroethylene	151	—	—	65.1	—	—
Ethylbenzene	81.3	—	—	38.7	—	—
Toluene	80.7	—	—	39.4	—	—
o-Xylene	97.9	—	—	50.8	—	—
1,4-Dichlorobenzene	110	—	—	74.9	—	—
Bromoform	131	—	—	104	—	—

Liquid Samples, Continued

Table C-11: Analytical Data - Experiment 6a (bagged, low temperature, low velocity, low height)

Compound	Influent (µg/L or 10^{+3} ppm)			Effluent (µg/L or 10^{+3} ppm)		
	Sample 1	Sample 2	Average	Sample 1	Sample 2	Average
Cyclohexane	77.0	---	---	48.2	---	---
Tetrachloromethane	115	---	---	69.3	---	---
Tetrachloroethylene	175	---	---	70.9	---	---
Ethylbenzene	64.9	---	---	50.1	---	---
Toluene	75.9	---	---	63.4	---	---
o-Xylene	85.6	---	---	67.7	---	---
1,4-Dichlorobenzene	94.0	---	---	84.3	---	---
Bromoform	108	---	---	134	---	---

Table C-12: Analytical Data - Experiment 6b (non-bagged, low temperature, low velocity, low height)

Compound	Influent (µg/L or 10^{+3} ppm)			Effluent (µg/L or 10^{+3} ppm)		
	Sample 1	Sample 2	Average	Sample 1	Sample 2	Average
Cyclohexane	79.3	---	---	34.7	---	---
Tetrachloromethane	105	---	---	45.7	---	---
Tetrachloroethylene	94.6	---	---	50.2	---	---
Ethylbenzene	55.2	---	---	34.1	---	---
Toluene	64.8	---	---	40.1	---	---
o-Xylene	71.2	---	---	45.4	---	---
1,4-Dichlorobenzene	87.6	---	---	62.0	---	---
Bromoform	128	---	---	104	---	---

Liquid Samples, Continued

Table C-13: Analytical Data - Experiment 7a (bagged, low temperature, high velocity, high height)

Compound	Influent (μg/L or 10^{+3} ppm)			Effluent (μg/L or 10^{+3} ppm)		
	Sample 1	Sample 2	Average	Sample 1	Sample 2	Average
Cyclohexane	36.6	32.9	34.8	28.2	—	—
Tetrachloromethane	99.1	145	122	84.6	—	—
Tetrachloroethylene	86.1	98.1	92.1	71.8	—	—
Ethylbenzene	43.7	44.3	44.0	38.1	—	—
Toluene	55.4	51.1	53.3	51.4	—	—
o-Xylene	58.7	52.4	55.6	54.9	—	—
1,4-Dichlorobenzene	66.5	81.8	74.2	65.6	—	—
Bromoform	124	118	121	124	—	—

Table C-14: Analytical Data - Experiment 7b (non-bagged, low temperature, high velocity, high height)

Compound	Influent (μg/L or 10^{+3} ppm)			Effluent (μg/L or 10^{+3} ppm)		
	Sample 1	Sample 2	Average	Sample 1	Sample 2	Average
Cyclohexane	46.3	—	—	31.2	—	—
Tetrachloromethane	108	—	—	77.4	—	—
Tetrachloroethylene	93.8	—	—	71.9	—	—
Ethylbenzene	50.9	—	—	39.9	—	—
Toluene	67.0	—	—	52.8	—	—
o-Xylene	60.5	—	—	50.3	—	—
1,4-Dichlorobenzene	61.5	—	—	53.2	—	—
Bromoform	124	—	—	113	—	—

Liquid Samples, Continued

Table C-15: Analytical Data - Experiment 8a (bagged, high temperature, high velocity, high height)

Compound	Influent (µg/L or 10^{+3} ppm)			Effluent (µg/L or 10^{+3} ppm)		
	Sample 1	Sample 2	Average	Sample 1	Sample 2	Average
Cyclohexane	57.3	---	---	33.9	---	---
Tetrachloromethane	89.6	---	---	65.1	---	---
Tetrachloroethylene	88.7	---	---	64.8	---	---
Ethylbenzene	66.2	---	---	52.5	---	---
Toluene	88.4	---	---	72.1	---	---
o-Xylene	74.6	---	---	61.8	---	---
1,4-Dichlorobenzene	58.3	---	---	53.2	---	---
Bromoform	131	---	---	114	---	---

Table C-16: Analytical Data - Experiment 8b (non-bagged, high temperature, high velocity, high height)

Compound	Influent (µg/L or 10^{+3} ppm)			Effluent (µg/L or 10^{+3} ppm)		
	Sample 1	Sample 2	Average	Sample 1	Sample 2	Average
Cyclohexane	79.0	---	---	50.4	33.0	41.7
Tetrachloromethane	106	---	---	64.5	81.7	73.1
Tetrachloroethylene	106	---	---	68.2	66.5	67.4
Ethylbenzene	86.4	---	---	57.2	48.8	53.0
Toluene	107	---	---	73.0	59.7	66.4
o-Xylene	94.8	---	---	67.4	60.7	64.1
1,4-Dichlorobenzene	72.8	---	---	52.8	66.6	59.7
Bromoform	158	---	---	129	124	127

Liquid Samples, Continued

Table C-17: Analytical Data - Repeat Experiment 3b (non-bagged, high temperature, low velocity, high height)						
Compound	Influent (µg/L or 10^{+3} ppm)			Effluent (µg/L or 10^{+3} ppm)		
	Sample 1	Sample 2	Average	Sample 1	Sample 2	Average
Cyclohexane	213	—	—	50.6	—	—
Tetrachloromethane	188	—	—	51.4	—	—
Tetrachloroethylene	192	—	—	74.8	—	—
Ethylbenzene	172	—	—	53.1	—	—
Toluene	88.1	—	—	28.5	—	—
o-Xylene	168	—	—	63.9	—	—
1,4-Dichlorobenzene	211	—	—	130	—	—
Bromoform	143	—	—	86.5	—	—

Table C-18: Analytical Data - Repeat Experiment 5b (non-bagged, high temperature, low velocity, low height)						
Compound	Influent (µg/L or 10^{+3} ppm)			Effluent (µg/L or 10^{+3} ppm)		
	Sample 1	Sample 2	Average	Sample 1	Sample 2	Average
Cyclohexane	244	—	—	52.9	—	—
Tetrachloromethane	160	—	—	34.3	—	—
Tetrachloroethylene	200	—	—	52.1	—	—
Ethylbenzene	150	—	—	53.0	—	—
Toluene	88.5	—	—	20.2	—	—
o-Xylene	154	—	—	44.7	—	—
1,4-Dichlorobenzene	219	—	—	88.5	—	—
Bromoform	143	—	—	54.5	—	—

Liquid Samples, Continued

Table C-19: Analytical Data - Repeat Experiment 1a (bagged, low temperature, high velocity, low height)

Compound	Influent (µg/L or 10^{+3} ppm)			Effluent (µg/L or 10^{+3} ppm)		
	Sample 1	Sample 2	Average	Sample 1	Sample 2	Average
Cyclohexane	57.2	62.4	59.8	46.5	43.3	44.9
Tetrachloromethane	92.6	93.0	92.8	75.1	80.4	77.8
Tetrachloroethylene	94.3	92.3	93.3	77.7	80.0	78.9
Ethylbenzene	122	69.7	95.9	63.0	61.6	62.3
Toluene	71.8	77.1	74.5	66.3	66.6	66.5
o-Xylene	77.1	77.3	77.2	74.4	74.8	74.6
1,4-Dichlorobenzene	92.4	91.7	92.1	91.7	90.0	90.9
Bromoform	122	119	121	124	121	123

Liquid Samples, Continued

Table C-20: Analytical Data - Experiment 9a Inactive Drain (bagged, low temperature)

Compound	Time: 0 hr (µg/L or 10^{+3} ppm)			Time 1 hr (µg/L or 10^{+3} ppm)		
	Sample 1	Sample 2	Average	Sample 1	Sample 2	Average
Cyclohexane	103	—	—	112	—	—
Tetrachloromethane	153	—	—	145	—	—
Tetrachloroethylene	166	—	—	162	—	—
Ethylbenzene	152	—	—	154	—	—
Toluene	132	—	—	134	—	—
o-Xylene	173	—	—	176	—	—
1,4-Dichlorobenzene	142	—	—	135	—	—
Bromoform	165	—	—	170	—	—
	Time: 4 hr (µg/L or 10^{+3} ppm)			Time 8 hr (µg/L or 10^{+3} ppm)		
	Sample 1	Sample 2	Average	Sample 1	Sample 2	Average
Cyclohexane	98.1	—	—	101	—	—
Tetrachloromethane	117	—	—	109	—	—
Tetrachloroethylene	142	—	—	147	—	—
Ethylbenzene	137	—	—	143	—	—
Toluene	117	—	—	112	—	—
o-Xylene	159	—	—	153	—	—
1,4-Dichlorobenzene	128	—	—	127	—	—
Bromoform	130	—	—	112	—	—
	Time: 24 hr (µg/L or 10^{+3} ppm)					
	Sample 1	Sample 2	Average			
Cyclohexane	85.6	77.2	81.4			
Tetrachloromethane	45.0	60.5	52.8			
Tetrachloroethylene	122	145	134			
Ethylbenzene	93.0	89.3	91.2			
Toluene	70.8	68.5	69.7			
o-Xylene	111	109	110			
1,4-Dichlorobenzene	112	108	110			
Bromoform	22.0	21.0	21.5			

Liquid Samples, Continued

Table C-21: Analytical Data - Experiment 9b Inactive Drain (non-bagged, low temperature)

Compound	Time: 0 hr (µg/L or 10^{+3} ppm)			Time 1 hr (µg/L or 10^{+3} ppm)		
	Sample 1	Sample 2	Average	Sample 1	Sample 2	Average
Cyclohexane	100	—	—	147	—	—
Tetrachloromethane	123	—	—	136	—	—
Tetrachloroethylene	134	—	—	139	—	—
Ethylbenzene	87.8	—	—	103	—	—
Toluene	92.9	—	—	96.5	—	—
o-Xylene	117	—	—	116	—	—
1,4-Dichlorobenzene	128	—	—	123	—	—
Bromoform	190	—	—	182	—	—
	Time: 4 hr (µg/L or 10^{+3} ppm)			Time 8 hr (µg/L or 10^{+3} ppm)		
	Sample 1	Sample 2	Average	Sample 1	Sample 2	Average
Cyclohexane	88.7	—	—	55.9	—	—
Tetrachloromethane	158	—	—	162	—	—
Tetrachloroethylene	149	—	—	124	—	—
Ethylbenzene	90.5	—	—	73.7	—	—
Toluene	86.5	—	—	70.0	—	—
o-Xylene	111	—	—	92.9	—	—
1,4-Dichlorobenzene	119	—	—	110	—	—
Bromoform	154	—	—	139	—	—
	Time: 24 hr (µg/L or 10^{+3} ppm)					
	Sample 1	Sample 2	Average			
Cyclohexane	89.0	—	—			
Tetrachloromethane	65.5	—	—			
Tetrachloroethylene	114	—	—			
Ethylbenzene	61.9	—	—			
Toluene	50.5	—	—			
o-Xylene	77.6	—	—			
1,4-Dichlorobenzene	118	—	—			
Bromoform	48.3	—	—			

Liquid Samples, Continued

Table C-22: Analytical Data - Experiment Aligned 1

(non-bagged, aligned, low temperature, high velocity, high height)

Compound	Influent (µg/L or 10^{+3} ppm)			Effluent (µg/L or 10^{+3} ppm)		
	Sample 1	Sample 2	Average	Sample 1	Sample 2	Average
Cyclohexane	30.6	—	—	21.4	—	—
Tetrachloromethane	79.3	—	—	62.5	—	—
Tetrachloroethylene	69.8	—	—	53.9	—	—
Ethylbenzene	37.7	—	—	30.8	—	—
Toluene	48.2	—	—	41.1	—	—
o-Xylene	43.7	—	—	38.7	—	—
1,4-Dichlorobenzene	57.7	—	—	55.9	—	—
Bromoform	85.7	—	—	82.5	—	—

Table C-22: Analytical Data - Experiment Aligned 2

(non-bagged, aligned, low temperature, high velocity, low height)

Compound	Influent (µg/L or 10^{+3} ppm)			Effluent (µg/L or 10^{+3} ppm)		
	Sample 1	Sample 2	Average	Sample 1	Sample 2	Average
Cyclohexane	39.3	—	—	30.8	—	—
Tetrachloromethane	99.4	—	—	61.0	—	—
Tetrachloroethylene	74.8	—	—	55.4	—	—
Ethylbenzene	45.3	—	—	39.1	—	—
Toluene	58.6	—	—	49.2	—	—
o-Xylene	53.2	—	—	46.7	—	—
1,4-Dichlorobenzene	60.3	—	—	51.6	—	—
Bromoform	101	—	—	92.7	—	—

Liquid Samples, Continued

Table C-23: Analytical Data - Experiment UT1
(non-bagged, aligned, 24°C, low flow (3.8 L/min), fall height 31 cm)

Compound	Influent (µg/L or 10^{+3} ppm)			Effluent (µg/L or 10^{+3} ppm)		
	Sample 1	Sample 2	Average	Sample 1	Sample 2	Average
Cyclohexane	67.7	56.5	62.10	38.7	38.2	38.5
Tetrachloromethane	96.2	83.2	89.7	51.9	50.8	51.4
Tetrachloroethylene	93.1	97.4	95.3	66.0	66.4	66.2
Ethylbenzene	63.7	61.9	62.8	44.7	44.4	44.6
Toluene	73.1	71.4	72.3	49.8	49.9	49.9
o-Xylene	81.6	78.5	80.1	58.7	60.2	59.5
1,4-Dichlorobenzene	91.9	93.7	92.8	69.2	73.0	71.1
Bromoform	125	121	123	102	109	105.5

Table C-24: Analytical Data - Experiment UT2
(non-bagged, aligned, 24°C, medium flow (7.6 L/min), fall height 31 cm)

Compound	Influent (µg/L or 10^{+3} ppm)			Effluent (µg/L or 10^{+3} ppm)		
	Sample 1	Sample 2	Average	Sample 1	Sample 2	Average
Cyclohexane	79.0	66.4	72.7	45.2	40.1	42.7
Tetrachloromethane	58.5	53.4	56.0	36.7	55.4	46.1
Tetrachloroethylene	87.5	86.9	87.2	66.6	60.2	63.4
Ethylbenzene	62.9	58.5	60.7	48.2	47.1	47.7
Toluene	67.1	65.5	66.3	52.5	46.8	49.7
o-Xylene	73.2	73.0	73.1	64.2	63.2	63.7
1,4-Dichlorobenzene	84.8	80.0	82.4	72.8	72.0	72.4
Bromoform	114	103	108.5	102	102	102

Liquid Samples, Continued

Table C-25: Analytical Data - Experiment UT3
(non-bagged, aligned, 24°C, high flow (11.4 L/min), fall height 31 cm)

Compound	Influent (µg/L or 10^{+3} ppm)			Effluent (µg/L or 10^{+3} ppm)		
	Sample 1	Sample 2	Average	Sample 1	Sample 2	Average
Cyclohexane	60.1	63.2	61.7	41.8	43.6	42.7
Tetrachloromethane	72.5	73.7	73.1	43.2	42.4	42.8
Tetrachloroethylene	88.9	87.7	88.3	71.6	67.6	69.6
Ethylbenzene	55.8	56.7	56.3	45.3	48.7	47.0
Toluene	60.7	61.2	61.0	53.0	51.9	52.5
o-Xylene	70.7	70.1	70.4	62.7	61.0	61.9
1,4-Dichlorobenzene	81.9	84.4	83.2	75.7	73.1	74.4
Bromoform	111	110	110.5	104	105	105

Table C-26: Analytical Data - Experiment UT4
(non-bagged, aligned, 24°C, low flow (3.8 L/min), fall height 62 cm)

Compound	Influent (µg/L or 10^{+3} ppm)			Effluent (µg/L or 10^{+3} ppm)		
	Sample 1	Sample 2	Average	Sample 1	Sample 2	Average
Cyclohexane	50.8	—	—	32.9	29.9	31.4
Tetrachloromethane	58.5	—	—	22.3	21.7	22.0
Tetrachloroethylene	82.6	—	—	44.0	45.7	44.9
Ethylbenzene	56.2	—	—	33.5	31.0	32.3
Toluene	60.9	—	—	38.0	39.0	38.5
o-Xylene	72.9	—	—	46.9	46.1	46.5
1,4-Dichlorobenzene	85.8	—	—	53.8	53.5	53.7
Bromoform	105	—	—	73.5	82.8	78.2

Liquid Samples, Continued

Table C-27: Analytical Data - Experiment UT5
(non-bagged, aligned, 24°C, high flow (11.4 L/min), fall height 62 cm)

Compound	Influent (µg/L or 10^{+3} ppm)			Effluent (µg/L or 10^{+3} ppm)		
	Sample 1	Sample 2	Average	Sample 1	Sample 2	Average
Cyclohexane	43.4	---	---	30.1	26.5	28.3
Tetrachloromethane	46.7	---	---	50.0	36.1	43.1
Tetrachloroethylene	70.9	---	---	59.9	59.2	59.6
Ethylbenzene	45.7	---	---	37.6	37.7	37.7
Toluene	55.1	---	---	47.5	44.4	46.0
o-Xylene	59.5	---	---	55.5	52.2	53.9
1,4-Dichlorobenzene	63.7	---	---	95.3	93.3	94.3
Bromoform	92.3	---	---	59.7	60.4	60.1

GAS SAMPLES

Table C-28: Analytical Data - Experiment 1a - Gas
(bagged, low temperature, high velocity, low height)

Compound	Concentration [ng/L, (ppmV @ 25 C)]			
	Sample 1	Sample 2	Average	Background
Cyclohexane	14200 (4.12)	---	---	9.00 (2.61 x 10^{-3})
Tetrachloromethane	31900 (5.06)	---	---	12.6 (2.00 x 10^{-3})
Tetrachloroethylene	14000 (2.06)	---	---	12.4 (1.83 x 10^{-3})
Ethylbenzene	6410 (1.48)	---	---	5.40 (1.25 x 10^{-3})
Toluene	8400 (2.23)	---	---	11.0 (2.92 x 10^{-3})
o-Xylene	5760 (1.33)	---	---	5.20 (1.20 x 10^{-3})
1,4-Dichlorobenzene	1910 (0.318)	---	---	4.00 (0.665 x 10^{-3})
Bromoform	990 (0.0957)	---	---	1.40 (0.135 x 10^{-3})

Table C-29: Analytical Data - Experiment 1a Repeat - Gas
(bagged, low temperature, high velocity, low height)

Compound	Concentration [ng/L, (ppmV @ 25 C)]		
	Sample 1	Sample 2	Average
Cyclohexane	45300 (13.2)	---	---
Tetrachloromethane	39300 (6.24)	---	---
Tetrachloroethylene	21200 (3.12)	---	---
Ethylbenzene	10200 (2.35)	---	---
Toluene	10300 (2.74)	---	---
o-Xylene	8180 (1.89)	---	---
1,4-Dichlorobenzene	2510 (0.417)	---	---
Bromoform	1010 (0.0976)	---	---

Gas Samples, Continued

Table C-30: Analytical Data - Experiment 2a - Gas
(bagged, low temperature, low velocity, high height)

Compound	Concentration [ng/L, (ppmV @ 25 C)]		
	Sample 1	Sample 2	Average
Cyclohexane	11700 (3.40)	—	—
Tetrachloromethane	45400 (7.21)	—	—
Tetrachloroethylene	24600 (3.62)	—	—
Ethylbenzene	8780 (2.02)	—	—
Toluene	11200 (2.98)	—	—
o-Xylene	8440 (1.95)	—	—
1,4-Dichlorobenzene	5630 (0.936)	—	—
Bromoform	1800 (0.174)	—	—

Table C-31: Analytical Data - Experiment 3a - Gas
(bagged, high temperature, low velocity, high height)

Compound	Concentration [ng/L, (ppmV @ 25 C)]		
	Sample 1	Sample 2	Average
Cyclohexane	18000 (5.23)	—	—
Tetrachloromethane	55800 (8.86)	—	—
Tetrachloroethylene	40400 (5.95)	—	—
Ethylbenzene	19100 (4.41)	—	—
Toluene	21900 (5.82)	—	—
o-Xylene	17800 (4.11)	—	—
1,4-Dichlorobenzene	12700 (2.11)	—	—
Bromoform	4090 (0.395)	—	—

Gas Samples, Continued

Table C-32: Analytical Data - Experiment 4a - Gas
(bagged, high temperature, high velocity, low height)

Compound	Concentration [ng/L, (ppmV @ 25 C)]		
	Sample 1	Sample 2	Average
Cyclohexane	24100 (7.00)	23900 (6.94)	24000 (6.97)
Tetrachloromethane	71300 (11.3)	68500 (10.9)	69900 (11.1)
Tetrachloroethylene	58500 (8.62)	49700 (7.32)	54100 (7.97)
Ethylbenzene	17500 (4.04)	16000 (3.69)	16750 (3.86)
Toluene	19400 (5.16)	17600 (4.68)	18500 (4.92)
o-Xylene	17400 (4.01)	15800 (3.65)	16600 (3.83)
1,4-Dichlorobenzene	10300 (1.71)	8820 (1.47)	9560 (1.59)
Bromoform	2760 (0.267)	2320 (0.224)	2540 (0.254)

Table C-33: Analytical Data - Experiment 5a - Gas
(bagged, high temperature, low velocity, low height)

Compound	Concentration [ng/L, (ppmV @ 25 C)]		
	Sample 1	Sample 2	Average
Cyclohexane	24000 (6.97)	—	—
Tetrachloromethane	41000 (6.51)	—	—
Tetrachloroethylene	37800 (5.57)	—	—
Ethylbenzene	16900 (3.90)	—	—
Toluene	18400 (4.89)	—	—
o-Xylene	19100 (4.41)	—	—
1,4-Dichlorobenzene	15500 (2.58)	—	—
Bromoform	3240 (0.313)	—	—

Gas Samples, Continued

Table C-34: Analytical Data - Experiment 6a - Gas
(bagged, low temperature, low velocity, low height)

Compound	Concentration [ng/L, (ppmV @ 25 C)]		
	Sample 1	Sample 2	Average
Cyclohexane	18700 (5.43)	---	---
Tetrachloromethane	24700 (3.92)	---	---
Tetrachloroethylene	17200 (2.53)	---	---
Ethylbenzene	7270 (1.68)	---	---
Toluene	8210 (2.18)	---	---
o-Xylene	7180 (1.66)	---	---
1,4-Dichlorobenzene	4720 (0.785)	---	---
Bromoform	1330 (0.128)	---	---

Table C-35: Analytical Data - Experiment 7a - Gas
(bagged, low temperature, high velocity, high height)

Compound	Concentration [ng/L, (ppmV @ 25 C)]		
	Sample 1	Sample 2	Average
Cyclohexane	23600 (6.85)	23000 (6.68)	23300 (6.77)
Tetrachloromethane	48400 (7.68)	48200 (7.65)	48300 (7.67)
Tetrachloroethylene	24600 (3.62)	22700 (3.34)	23650 (3.48)
Ethylbenzene	7060 (1.63)	8990 (2.07)	6870 (1.58)
Toluene	8340 (2.22)	6680 (1.78)	8340 (2.22)
o-Xylene	6350 (1.46)	5940 (1.37)	6145 (1.42)
1,4-Dichlorobenzene	3360 (0.559)	3010 (0.501)	3185 (0.530)
Bromoform	1270 (0.123)	1220 (0.118)	1245 (0.120)

Gas Samples, Continued

Table C-36: Analytical Data - Experiment 8a - Gas
(bagged, high temperature, high velocity, high height)

Compound	Concentration [ng/L, (ppmV @ 25 C)]		
	Sample 1	Sample 2	Average
Cyclohexane	37200 (10.8)	—	—
Tetrachloromethane	48700 (7.73)	—	—
Tetrachloroethylene	33500 (4.93)	—	—
Ethylbenzene	18900 (4.36)	—	—
Toluene	22700 (6.03)	—	—
o-Xylene	16900 (3.90)	—	—
1,4-Dichlorobenzene	7740 (1.29)	—	—
Bromoform	3100 (0.300)	—	—

Table C-37: Analytical Data - Experiment 9a - Gas
(bagged, inactive drain, low temperature)

Compound	Time = 1 hr [ng/L, (ppmV @ 25C)]			Time = 24 hr [ng/L, (ppmV @ 25 C)]		
	Sample 1	Sample 2	Avg	Sample 1	Sample 2	Avg
Cyclohexane	776 (0.225)	—	—	10.8 (3.14×10^{-3})	—	—
Tetrachloromethane	731 (0.116)	—	—	17.8 (2.83×10^{-3})	—	—
Tetrachloroethylene	523 (0.0770)	—	—	55.0 (8.10×10^{-3})	—	—
Ethylbenzene	260 (0.0600)	—	—	27.2 (6.28×10^{-3})	—	—
Toluene	233 (0.0619)	—	—	23.4 (6.22×10^{-3})	—	—
o-Xylene	276 (0.0637)	—	—	25.2 (5.81×10^{-3})	—	—
1,4-Dichlorobenzene	264 (0.0439)	—	—	51.0 (8.48×10^{-3})	—	—
Bromoform	33.6 (3.25×10^{-3})	—	—	6.40 (0.619×10^{-3})	—	—

Appendix D

Emission Factors (Misaligned Drain) for Individual Contaminants From Stripping Efficiency Experiments

Notes on emissions:

- Bagged emissions based on liquid influent concentrations and gas phase effluent concentrations.
- Inactive drain emissions:
  - Bagged emissions based on gas emissions at 1 hour
  - Non-bagged emissions range based on liquid concentrations over ranges 0-1 hours, 0-4 hrs, 0-8 hrs and 0-24 hrs.

Cyclohexane H = 7.17 @ 25 C		% Emissions			
		Low Velocity		High Velocity	
		Bagged	Non-bagged	Bagged	Non-bagged
Low Temp	Low Height	17	56	44	32
	High Height	18	56	48	33
High Temp	Low Height	26	64	58	35
	High Height	50	66	47	47
Inactive Drain (low temp)		bagged: 30 %/hr; non-bagged: -47 to 7.0 %/hr			

Tetrachloromethane H = 1.23 @ 25 C		% Emissions			
		Low Velocity		High Velocity	
		Bagged	Non-bagged	Bagged	Non-bagged
Low Temp	Low Height	15	57	29	32
	High Height	21	51	28	28
High Temp	Low Height	21	71	43	57
	High Height	31	59	39	31
Inactive Drain (low temp)		bagged: 23%/hr; non-bagged: -10 to 2.6 %/hr			

Tetrachloroethylene H = 0.72 @ 25 C		% Emissions			
		Low Velocity		High Velocity	
		Bagged	Non-bagged	Bagged	Non-bagged
Low Temp	Low Height	7.0	47	16	21
	High Height	11	69	18	23
High Temp	Low Height	27	66	38	29
	High Height	25	58	27	37
Inactive Drain (low temp)		bagged: 15%/hr; non-bagged: -3.8 to 1.0 %/hr			

Ethylbenzene H = 0.32 @ 25 C		% Emissions			
		Low Velocity		High Velocity	
		Bagged	Non-bagged	Bagged	Non-bagged
Low Temp	Low Height	8.0	38	9.0	21
	High Height	10	44	11	22
High Temp	Low Height	18	59	23	24
	High Height	15	59	21	39
Inactive Drain (low temp)		bagged: 8.2 %/hr; non-bagged: -17 to 2.2 %/hr			

Toluene H = 0.26 @ 25 C		% Emissions			
		Low Velocity		High Velocity	
		Bagged	Non-bagged	Bagged	Non-bagged
Low Temp	Low Height	8.0	38	10	23
	High Height	10	45	12	22
High Temp	Low Height	19	64	19	27
	High Height	17	64	18	38
Inactive Drain (low temp)		bagged: 8.4 %/hr; non-bagged: -3.9 to 3.5 %/hr			

O-Xylene H = 0.20 @ 25 C		% Emissions			
		Low Velocity		High Velocity	
		Bagged	Non-bagged	Bagged	Non-bagged
Low Temp	Low Height	6.0	36	7.5	16
	High Height	8.0	41	8.0	17
High Temp	Low Height	16	60	18	17
	High Height	14	55	16	32
Inactive Drain (low temp)		bagged: 7.7 %/hr; non-bagged: 0.85 to 2.8 %/hr			

1,4-Dichlorobenzene H = 0.13 @ 25 C		% Emissions			
		Low Velocity		High Velocity	
		Bagged	Non-bagged	Bagged	Non-bagged
Low Temp	Low Height	4.0	29	2.5	23
	High Height	3.0	-4.5	3.0	14
High Temp	Low Height	12	46	9.0	13
	High Height	9.0	39	10	18
Inactive Drain (low temp)		bagged: 9.5 %/hr; non-bagged: 0.3 to 3.9 %/hr			

Bromoform H = 0.02 @ 25 C		% Emissions			
		Low Velocity		High Velocity	
		Bagged	Non-bagged	Bagged	Non-bagged
Low Temp	Low Height	1.0	19	1.0	7.0
	High Height	1.0	6.4	1.0	8.9
High Temp	Low Height	2.0	41	2.0	5.0
	High Height	2.0	32	2.0	20
Inactive Drain (low temp)		bagged: 1.0 %/hr; non-bagged: 3.8 to 5.6 %/hr			

APPENDIX E

Degree of Saturation in Gas Phase During Bagged Experiments From Stripping Efficiency Experiments

Experimental Identification for emission factor experiments

		% Emissions			
		Low Velocity		High Velocity	
		Bagged	Non-bagged	Bagged	Non-bagged
Low Temp	Low Height	6a	6b	1a	1b
	High Height	2a	2b	7a	7b
High Temp	Low Height	5a	5b	4a	4b
	High Height	3a	3b	8a	8b
Inactive Drain (low temp)		9a (bagged), 9b (unbagged)			

Degree of Saturation - Calculation Used:

Degree of Saturation = Cgas / Cg*

where:

Cgas: actual gas phase concentration of contaminant

Cg*: gas phase concentration if gas is in equilibrium with liquid phase

$Cg^* = H_t * C_l$

where:

H_t: Henry's partition coefficient value adjusted to process water temperature

C_l: contaminant liquid phase concentration

$H_t = H_{25} * 1.044^{(T-25)}$

where:

H_{25}: Henry's partition coefficient value at 25 °C

T: process water temperature (°C)

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Table E-1: Degree of Saturation In Gas Phase For Bagged Experiments

	Degree of Saturation (%)			
Experiment	1a	2a	3a	4a
Cyclohexane	9.2	11	7.8	9.7
Tertrachloromethane	34	52	35	43
Tetrachloroethylene	47	58	54	55
Ethylbenzene	51	69	67	66
Toluene	68	84	85	67
o-Xylene	63	79	88	76
1,4-Dichlorobenzene	21	40	69	54
Bromoform	54	62	85	59
Experiment	5a	6a	7a	8a
Cyclohexane	7.3	6.7	14	8.0
Tertrachloromethane	51	36	58	32
Tetrachloroethylene	56	42	57	38
Ethylbenzene	65	56	70	59
Toluene	82	62	80	64
o-Xylene	85	66	69	72
1,4-Dichlorobenzene	73	53	46	59
Bromoform	99	61	62	71
Experiment	9a (1hr)	9a(24 hr)	1a repeat	
Cyclohexane	0.1	<0.1	18	
Tertrachloromethane	0.4	< 0.1	51	
Tetrachloroethylene	0.5	< 0.1	46	
Ethylbenzene	0.6	0.1	64	
Toluene	0.7	0.1	74	
o-Xylene	0.8	0.1	68	
1,4-Dichlorobenzene	1.6	0.3	26	
Bromoform	1.0	1.3	51	

Appendix F

Mass Emission Calculations Based on OVA Readings

(Reproduced from EPA Document: EPA-453/R-95-017)

TABLE 4-1. CALCULATION PROCEDURES FOR LEAK RATE WHEN USING THE VACUUM METHOD

$$\underset{(\text{kg/hr})}{\text{Leak Rate}} = \frac{9.63 \times 10^{-10}\ (Q)(MW)(GC)(P)}{T + 273.15} + \frac{(\rho)(V_L)}{16.67(t)}$$

where:

9.63×10^{-10} = A conversion factor using the gas constant:

$$\frac{°K \times 10^{6} \times \text{kg-mol} \times \text{min}}{\ell \times \text{hour} \times \text{mmHg}};$$

Q = Flow rate out of bag (ℓ/min);

MW^{a} = Molecular weight of organic compound(s) in the sample bag[c] or alternatively in the process stream contained within the equipment piece being bagged (kg/kg-mol);

GC^{b} = Sample bag organic compound concentration (ppmv) minus background bag organic compound concentration[c] (ppmv);

P = Absolute pressure at the dry gas meter (mmHg);

T = Temperature at the dry gas meter (°C);

ρ = Density of organic liquid collected (g/mℓ);

V_L = Volume of liquid collected (mℓ);

16.67 = A conversion factor to adjust term to units of kilograms per hour (g × hr)/(kg × min)

t = Time in which liquid is collected (min); and

---

[a] For mixtures calculate MW as:

$$= \sum_{i=1}^{n} MW_i\ X_i \ / \ \sum_{i=1}^{n} X_i$$

where:

MW_i = Molecular weight of organic compound i;
X_i = Mole fraction of organic compound i; and
n = Number of organic compounds in mixture.

[b] For mixtures, the value of GC is the total concentration of all the organic compounds in the mixture.

[c] Collection of a background bag is optional. If a background bag is not collected, assume the background concentration is zero.

TABLE 4-2. CALCULATION PROCEDURES FOR LEAK RATE WHEN USING THE BLOW-THROUGH METHOD

$$\text{Leak Rate (kg/hr)} = \left(\frac{1.219 \times 10^{-5}\ (Q)\ (MW)\ (GC)}{T + 273.15} + \frac{(\rho)\ (V_L)}{16.67\ (t)} \right) \times \left(\frac{10^6 \text{ppmv}}{10^6 \text{ppmv-GC}} \right)$$

where:

1.219×10^{-5} = A conversion factor taking into account the gas constant and assuming a pressure in the tent of 1 atmosphere:

$$\frac{^{o}K \times 10^6 \times \text{kg-mol}}{m^3};$$

Q = flow rate out of tent (m^3/hr);

$$= \frac{N_2 \text{ Flow Rate } (\ell/\text{min})}{1 - [\text{Tent Oxygen Conc. (volume \%)}/21]} \times \frac{[0.06\ (m^3/\text{min})]}{(\ell/\text{hr})}$$

MW[a] = Molecular weight of organic compounds in the sample bag or alternatively in the process stream contained within the equipment piece being bagged (kg/kg-mol);

GC[b] = Sample bag organic compound concentration (ppmv), corrected for background bag organic compound concentration (ppmv);[c]

T = Temperature in tent (^{o}C);

ρ = Density of organic liquid collected (g/mℓ);

V_L = Volume of liquid collected (mℓ);

16.67 = A conversion factor to adjust term to units of Kilograms per hour (g × hr)/(kg × min); and

t = Time in which liquid is collected (min).

---

[a] For mixtures calculate MW as:

$$= \sum_{i=1}^{n} MW_i\ x_i \ / \ \sum_{i=1}^{n} x_i$$

where:

MW_i = Molecular weight of organic compound i;

TABLE 4-2. CALCULATION PROCEDURES FOR LEAK RATE WHEN USING THE BLOW-THROUGH METHOD (Continued)

X_i = Mole fraction of organic compound i; and
n = Number of organic compounds in mixture.

[b] For mixtures, the value of GC is the total concentration of all the organic compounds in the mixture.

[c] Collection of a background bag is optional. If a background bag is not collected, assume the background concentration is zero. To correct for background concentration, use the following equation:

$$\underset{(\text{ppmv})}{GC} = SB - \left(\frac{TENT}{21} \times BG\right)$$

where:

SB = Sample bag concentration (ppmv);
TENT = Tent oxygen concentration (volume %); and
BG = Background bag concentration (ppmv)

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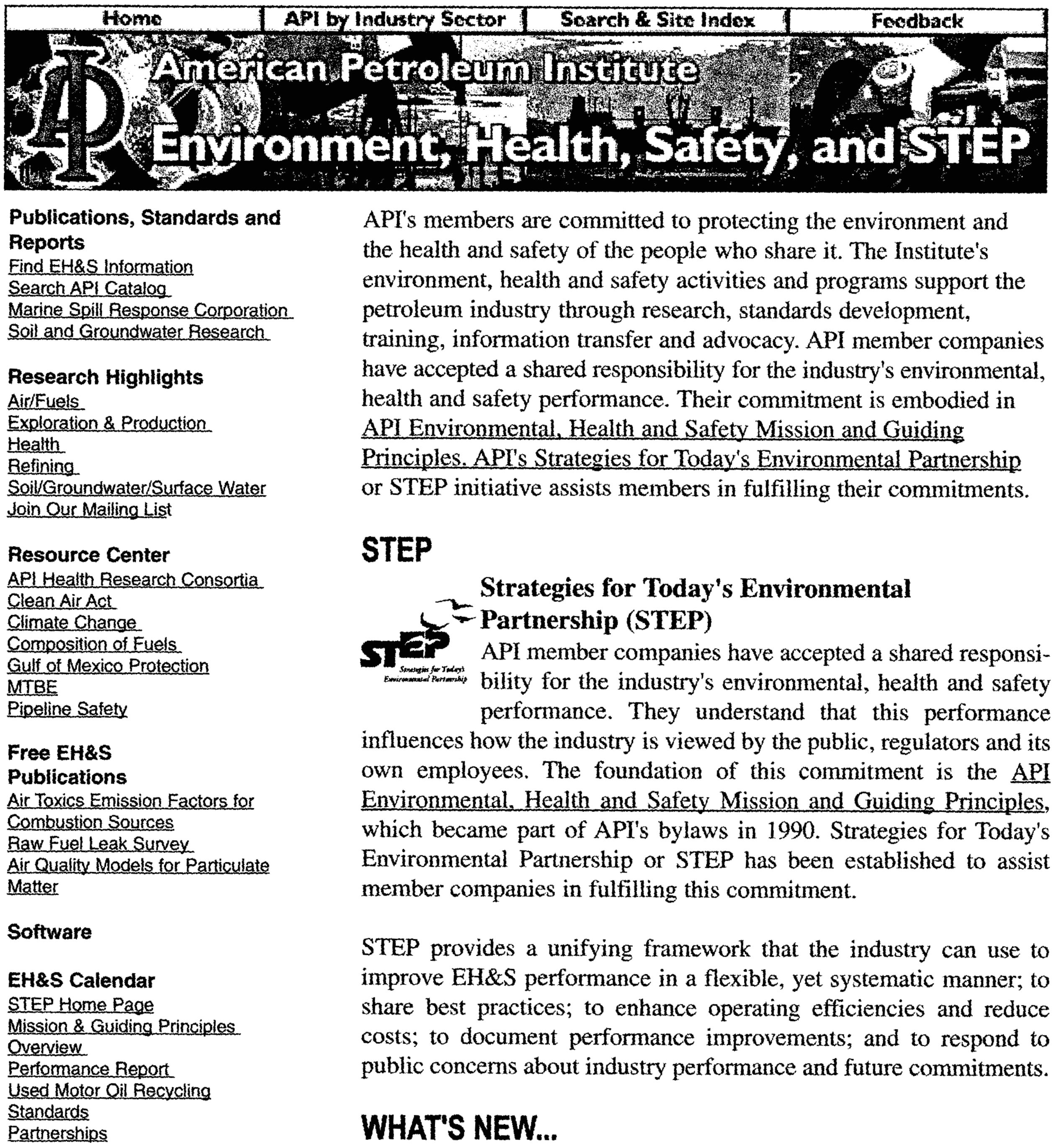

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