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STEP
Strategies for Today's Environmental Partnership

Development of Emission Factors for Leaks in Refinery Components in Heavy Liquid Service

Health and Environmental Affairs Department
Publication Number 337
August 1996

STEP
Strategies for Today's Environmental Partnership

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Development of Emission Factors For Leaks in Refinery Components in Heavy Liquid Service

Health and Environmental Affairs Department

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ABSTRACT

The objective of this program was to develop a set of emission factors (expressed in lb/hr/component) applicable to refinery components (valves, flanged connectors, non-flanged connectors, pumps, open-ended lines, and others) in heavy liquid (HL) service. To accomplish this, more than 211,000 existing HL screening values from Southern California refineries were compiled and compared with 2,500 new HL screening measurements taken at two refineries in Washington State. Southern California is under stringent emission control regulations due to extreme non-attainment of the National Ambient Air Quality Standards (NAAQS); thus, its screening data may not be representative of refineries without stringent fugitive emission controls. However, the Southern California screening data were compared to screening measurements made at refineries in Washington State, which is an area in attainment of the NAAQS and therefore without fugitive emissions control. There was no significant statistical difference found in emission factors between the two areas; the results suggest there is no difference in emissions from heavy liquid components in areas with and without leak detection and repair (LDAR) programs. The new emission factors range from 65% to 86% less than the current EPA emission factors.

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EXECUTIVE SUMMARY

This report presents the results of a study to develop emission factors applicable to refinery components in heavy liquid (HL) service. It includes an analysis of whether the type of distillate or residual hydrocarbon in the stream would influence the emission factors. The objectives were accomplished using existing screening data for components in HL service and confirming those data with new screening data obtained from refineries without Leak Detection and Repair (LDAR) programs. These factors, expressed in pounds/hour/component, are such that they can be multiplied by the number of individual components in HL service in a refinery to calculate the volatile organic compound (VOC) emissions due to leaks from those components. Extensive statistical analysis of the screening data and related process parameters was performed.

TECHNICAL APPROACH

Refineries in Southern California (SoCal) were solicited for available HL screening data. Four refineries responded, providing 211,290 discrete screening values. Leak Detection and Repair has been practiced at these refineries for approximately ten years on components in gas (G) and light liquid (LL) service, <u>but not for HL service</u>. Nevertheless, because SoCal has tight emission controls, it was decided to conduct additional HL component screenings in an area without LDAR to determine whether or not the SoCal HL screening values were representative. The site chosen for the HL screenings was Washington State, which is in attainment for all of the National Ambient Air Quality Standards for VOCs and where LDAR programs are not required except for new or modified facilities under the New Source Performance Standards (NSPS). More than 2,500 discrete values were recorded from which the average emission factors for each component category were computed. A sampling matrix was used for the Washington test which would cover a representative range of middle distillate and residual process streams. These data were compared to values from SoCal to assess whether they were representative of all refineries.

CONCLUSIONS

The screening tests performed as part of the program showed that the emission factors for the refineries in Southern California, for which HL screening data were available, were similar to emission factors determined based on measurements at the Washington State refineries. Both sets of emission factors are lower than those published in EPA's "Protocol for Equipment Leak Estimates," Contract 68-d1-0117, for EPA by Radian Corp., June 1993 (EPA 1993). The Washington State factors are lower than those from Southern California for all components with the exception of pumps. The higher pump value in Washington State was influenced by one pump leaking at a high rate.

The screening values for components in HL service were found to be independent of stream temperature and hydrocarbon composition (as defined by the 10% Distillation Temperature, ASTM Method D86). At first this may seem odd. The heavy liquid streams range from kerosene to asphalt. Intuitively, kerosene should leak more than asphalt. However, a reasonable explanation of this observed phenomenon is that the heavier hydrocarbons, which are more viscous and less volatile at ambient temperatures, inherently circulate in higher temperature process streams. Therefore, for the medium-weight middle distillate, the heavy-weight middle distillate, and the heavy residual streams, it appears that the viscosity and vapor pressure (properties that affect leakage) have a similar effect on the screening values.

In this report, the SoCal data are presented and discussed along with the details of the Washington State tests. An extensive statistical analysis of the various data sets is presented in Appendix A discussing various methods of combining the data to derive emission factors. The conclusions reached as a result of the statistical analysis follow:

- <u>The SoCal data have a similar distribution of emission rates from quarter to quarter.</u> Therefore, in aggregating screening data from different refineries, where individual refineries have different amounts of data (i.e., 2 quarters, 6 quarters and 7 quarters), the individual refinery data sets were reduced by averaging repeated measurements for each component.

- <u>The analysis of the Washington State screening data indicates that there is a significant difference in emission factors among component types (e.g., valve, pump)</u>. However, the differences in emission factors among the various HL stream types (i.e., medium middle distillate, heavy middle distillate and heavy residual) are not considered to be statistically significant.

- The emission factors for the SoCal refineries and the Washington refineries are statistically similar. (For all components except pump seals, the respective emission factors for the Washington refineries are slightly lower than those for the SoCal refineries.) This serves to demonstrate that there should be no significant differences in HL emission factors between areas with and without LDAR programs, indicating that the HL emission factors generated by these screening data should be universally applicable to refineries in the U.S.

Table ES-1 presents two sets of factors derived using a two-step averaging method, as discussed in Appendix A, one based exclusively on SoCal data (where the quantity of data is large) and one based on a combination of SoCal and Washington data. These are compared to the factors currently published in EPA's Protocol document. API recommends the use of the combined emission factors. This data set is representative of refineries both with and without LDAR programs. The statistical analysis shows no significant difference between the data sets.

Table ES-1. Emission Factors for Components in HL Service

Component Type	**Emission Factor SoCal Data, lb/hr/component**	**Emission Factor Combined SoCal & Washington Data, lb/hr/component**	**Emission Factor EPA Protocol (1980 Ref. Study), lb/hr/component**
Valve	2.13E-04	1.76E-04	5.07E-04
Fitting	9.49E-05	7.93E-05	5.51E-04
Flange	9.66E-05	7.00E-05	5.51E-04
Pump	7.63E-03	8.25E-03	4.63E-02
Open-Ended Line	--	1.86E-05	--
Other	1.14E-04	6.21E-05	--

Section 1
INTRODUCTION

BACKGROUND

Estimating air pollutants from stationary sources is necessary for compiling emission inventories, determining emission fees, and meeting the conditions of various permits and compliances. Extensive field measurements have been made over the last four years to develop more accurate emission correlation and emission factor data for estimating emissions from leaking pipeline components. For any petroleum industry facility employing leak detection and repair (LDAR) procedures, the component-leak emissions can be estimated using the recorded screening values expressed in parts per million (ppmv) along with component-specific correlation equations approved by EPA and found on its Technology Transfer Network (TTN) bulletin board (EPA TTN, 1995). For certain types of facilities where LDAR is not practiced, such as oil production fields and bulk terminals, EPA emission factors are readily available for use in estimating emissions.

Pipeline components in heavy liquid (HL) service are generally not included in LDAR programs regardless of the facility. Since HL screening values are generally not available, it is necessary to use EPA's emissions factors. The HL emission factors published in EPA's 1993 *Protocol for Equipment Leak Estimates* (EPA, 1993) were believed to be high, based on available information. Therefore, API conducted a study to develop more accurate HL emission factors.

OBJECTIVE

The objective of the program was to develop the emission factors and to determine whether or not the type of distillate or residual hydrocarbon in the HL stream would influence the emission factors. Emission factor data were obtained and extensive statistical analysis of the screening data and related process parameters was performed and discussed.

APPROACH

Refineries in Southern California (SoCal) were solicited for available HL screening data. Four refineries responded, providing 211,000 discrete HL screening values. At those refineries, LDAR has been practiced for approximately ten years on components in gas (G) and light liquid (LL) service, but not generally for HL service. Nevertheless, because SoCal has tight emission controls, additional HL component screenings were conducted in an area without LDAR to determine whether or not the SoCal HL screening values were representative. Two refineries in Washington State were chosen for the HL screenings. Washington is in attainment of the National Ambient Air Quality Standards and LDAR programs are not required except for new or modified facilities under the New Source Performance Standards (NSPS). More than 2,500 discrete values were recorded from which the average emission factors for each component category were computed. The Washington test used a sampling matrix which covered a representative range of middle distillate and residual process streams.

REPORT ORGANIZATION

Section 2 presents the SoCal data from four refineries showing leak rate distribution and average emission rates for various components. Section 3 presents the Washington State refinery data including the screening values, leak rate distribution, average emissions and the effects of stream composition and temperature on leak rate. Section 4 presents the conclusions. The statistical treatment of the SoCal, Washington and aggregated data is presented in Appendix A and the discrete screening and associated measurements, taken at the Washington refineries, are tabulated in Appendix B.

Section 2

DATA FROM SOUTHERN CALIFORNIA REFINERIES

Four sets of existing screening data, received from SoCal refineries, were used to derive the refinery HL component emission factors. The refineries are designated C1, C2, C3, and C4, respectively. Refinery C1 provided 165,852 values of HL screening data in electronic format. The data were taken over seven quarters, from 1992 to 1994. Refinery C1 has a full LDAR program and had screened the HL components along with G & LL service components in accordance with South Coast Air Quality Management District's (SCAQMD) Rule 1173 even though the screening of HL components has never been required by the SCAQMD. The data were taken with a Foxboro Model 108 Organic Vapor Analyzer (OVA) with strict Quality Control (QC) procedures in accordance with EPA Method 21, which stipulates that the OVA probe is maintained at the surface of the component being screened.

Refinery C2 provided 21,410 HL screening values for six quarters also over 1992 to 1994. This refinery had been screening HL components in addition to conducting its SCAQMD Rule 1173 program. Data from Refinery C3 and C4 were originally obtained in electronic format during a WSPA/API study in 1992 as part of the planning effort for the 1993 refinery screening and bagging study (Radian Corp., 1992). These screening values, which included various component types and services, were measured in the initial two quarters of the Rule 1173 program in 1991. In reviewing the data, it was found that two of the refineries had included HL screening data. The C3 and C4 data set, when merged, comprised a total of 24,028 screening values.

The screening values in the three data sets were converted to emission rates using the latest set of correlation equations and zero and pegged source emission factors accepted by EPA and posted on EPA's TTN (EPA TTN, 1995), which are presented in Table 2-1.

Table 2-1. Correlation Equations, Default Zero Emission Rates, and Pegged Emission Rates Used For Emissions Calculations (EPA TTN Bulletin Board, 1995)

Equipment Type/Service	Default Zero Emission Rate (lb/hr/comp)	Pegged Emission Rates (lb/hr/comp)		Correlation Equation[a]
		10,000 ppmv	100,000 ppmv	
Connector/All	1.65E-05	0.062	0.066	$E = 3.33E\text{-}06 \times (SV)^{0.735}$
Flange/All	6.84E-07	0.19	0.19	$E = 9.79E\text{-}06 \times (SV)^{0.703}$
Open-Ended Line/All	4.41E-06	0.66	0.17	$E = 4.76E\text{-}06 \times (SV)^{0.704}$
Pump/All	5.29E-05	0.16	0.35[b]	$E = 1.06E\text{-}04 \times (SV)^{0.610}$
Valve/All	1.72E-05	0.14	0.31	$E = 5.03E\text{-}06 \times (SV)^{0.746}$
Other[c]/All	8.80E-06	0.16	0.24	$E = 2.91E\text{-}06 \times (SV)^{0.589}$

[a] E is the predicted mass emission rate (lb/hr) and SV is the screening value (ppmv) measured by the monitoring device.

[b] Only 2 data values were available for the pump over-100,000 emission factor. Therefore, the pump over-100,000 ppmv emission factor was obtained by multipling by the over-100,000 ppmv emission factor for "other" by the ratio, pump/other at the over-100,000 ppmv level.

[c] The "other" equipment type includes instrument, loading arms, pressure relief valves, stuffing boxes, vents, compressors, and dump lever arms.

Table 2-2 summarizes the SoCal component-leak emission data, showing the total number of components of each type screened, the total estimated emissions using the Table 2-1 conversion, and the average emission factor obtained by dividing the total emissions by the number of components. Values are presented for each of the three data sets. In each case the average emission factors computed are compared to the 1980 refinery HL emission factors as presented in EPA's June 1993 Protocol document.

Table 2-2. Average Emission Factors for Components in Heavy Liquid Service
(7 Qtrs. of Refinery C1 Data, 6 Qtrs. of Refinery C2 data, and 2 Qtrs. of Refineries C3 & C4 data)

Refinery C1 data					
Component	**Service**	**Count**	**Total Emissions (EPA August 1995) (lb/hr)**	**Average Emission Factor (lb/hr/comp)**	**1980 Refinery (lb/hr/comp)**
Valve	HL	28,265	0.8782	3.11E-05	5.07E-04
Fitting	HL	100,482	1.8313	1.82E-05	5.51E-04
Flange	HL	23,370	1.1716	5.01E-05	5.51E-04
Pump	HL	787	0.4364	5.54E-04	4.63E-02
Other	HL	12,077	1.3669	1.13E-04	--
PRD	HL	871	0.0984	1.13E-04	--
	Total =	165,852			
Refinery C2 data					
Component	**Service**	**Count**	**Total Emissions (EPA August 1995) (lb/hr)**	**Average Emission Factor (lb/hr/comp)**	**1980 Refinery (lb/hr/comp)**
Valve	HL	5,468	0.8456	1.55E-04	5.07E-04
Fitting	HL	14,268	0.2626	1.84E-05	5.51E-04
Flange	HL	1,536	0.2192	1.43E-04	5.51E-04
Pump	HL	72	0.1070	1.49E-03	4.63E-02
PRD	HL	66	0.0006	8.71E-06	--
	Total =	21,410			
Refinery C3 & C4 data					
Component	**Service**	**Count**	**Total Emissions (EPA August 1995) (lb/hr)**	**Average Emission Factor (lb/hr/comp)**	**1980 Refinery (lb/hr/comp)**
Valve	HL	10,137	3.5001	3.45E-04	5.07E-04
Fitting	HL	13,312	2.1927	1.65E-04	5.51E-04
Pump	HL	116	1.6503	1.42E-02	4.63E-02
PRD	HL	463	0.0499	1.08E-04	--
	Total =	24,028			

Figures 2-1, 2-2, 2-3, and 2-4 show the distribution of the screening values for the aggregate of all components, for the four refineries, in screening ranges of less than 10 ppmv, 10 to 99 ppmv, 100 to 999 ppmv, etc. As can be seen, the percentage of components screening greater than 1,000 ppmv ranges from 0.02 to 0.7 percent.

Refer to Appendix A for further analysis of these data.

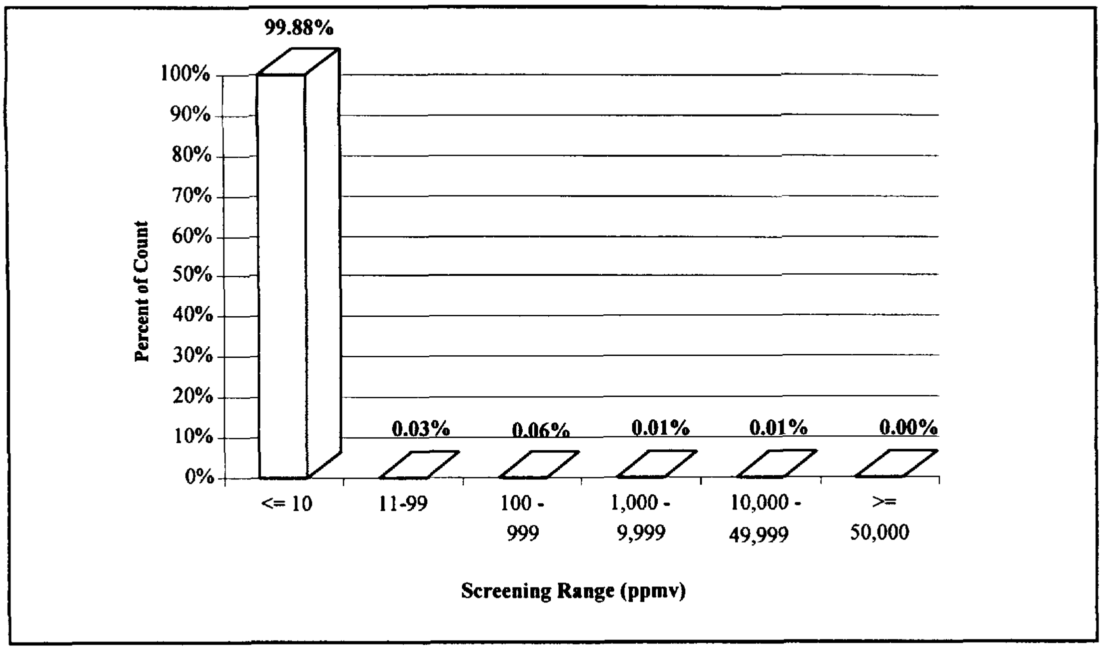

Figure 2-1. HL Component Leak Rate Distribution - Refinery C1 (165,852 values)

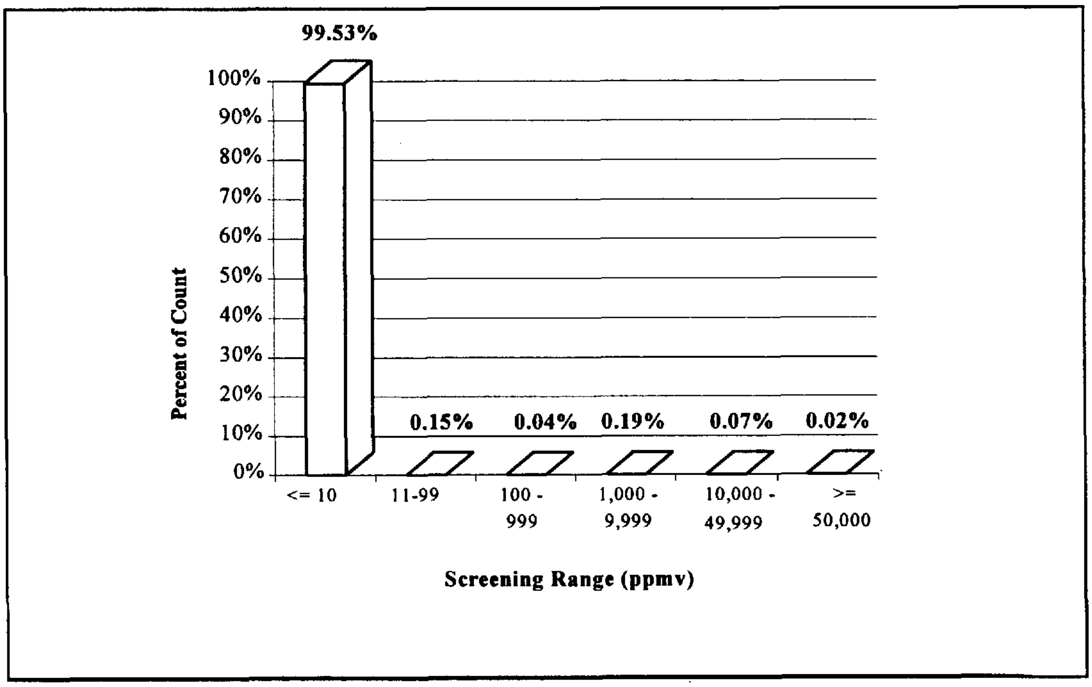

Figure 2-2. HL Component Leak Rate Distribution - Refinery C2 (21,410 values)

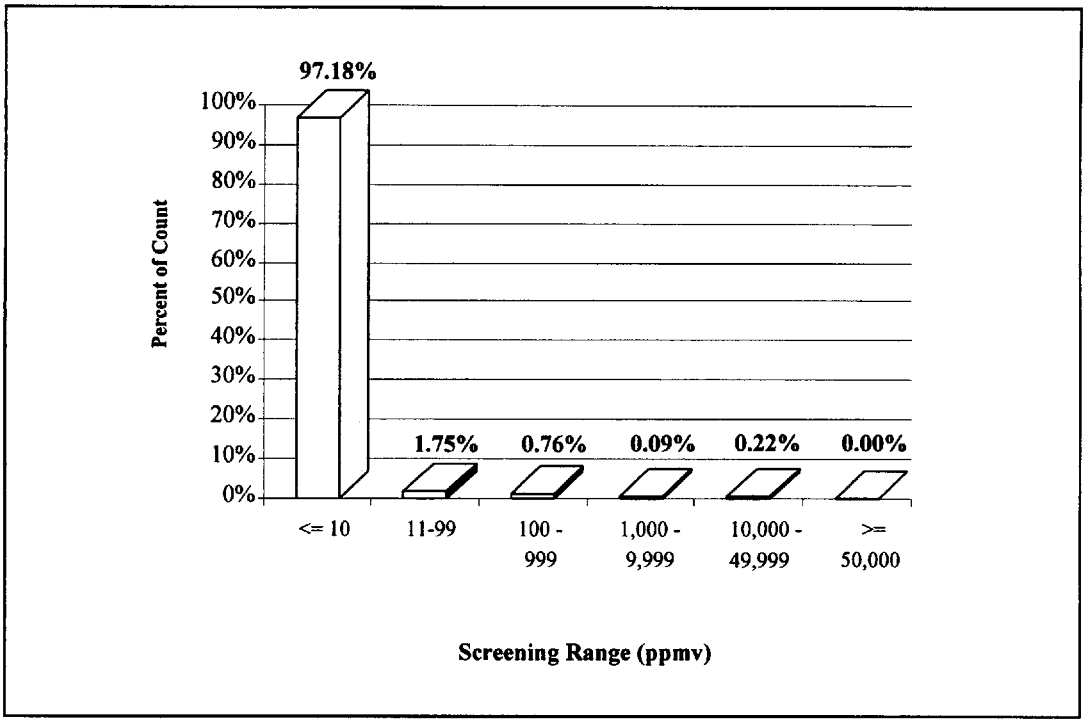

Figure 2-3. HL Component Leak Rate Distribution - Refinery C3 (7,767 values)

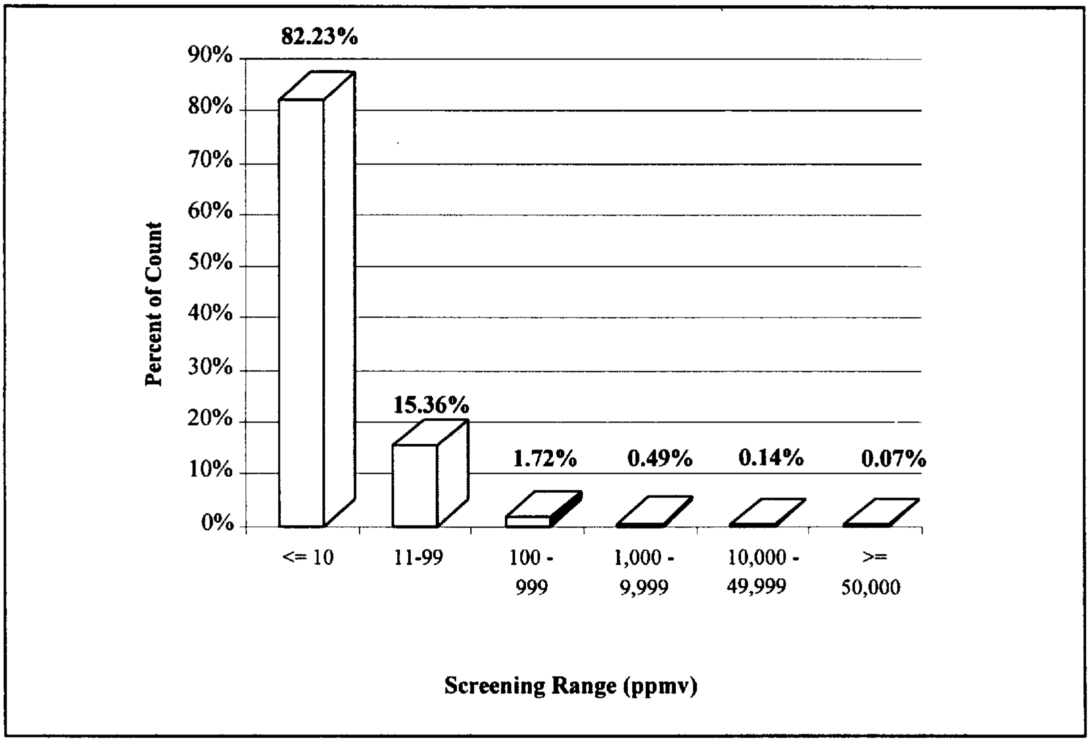

Figure 2-4. HL Component Leak Rate Distribution - Refinery C4 (16,261 values)

Section 3

NEW SCREENING DATA FROM WASHINGTON STATE REFINERIES

To obtain representative data, a matrix was prepared for the screening tests to be performed, as shown in Table 3-1. The number in each square of the matrix represents the target number of screening tests to be performed at two Washington State refineries designated Refineries "W1" and "W2". The basis for this matrix was 350 screenings per day. This is a relatively low screening rate because each component had to be properly identified (the components were not ID tagged) and certain stream properties (10% distillation point and type) and process parameters (temperature and pressure) had to be recorded.

Table 3-1. Washington State Test Matrix

Component	Type of Heavy Liquid Service		
Type	Middle Distillate, medium*	Middle Distillate, heavy*	Heavy Residual - #6
Valves	600	600	15
Fittings & Flanges	600	600	15
Pumps	12	12	4

* A definition of middle distillate medium & heavy service is as follows:

Middle Distillate - Medium is defined as streams with a 10% distillation temperature between 300 °F and 500°F including such products as:

- Commercial Jet Fuel
- SR Kerosene
- Hydro-Desulfurized Jet/Kero
- Diesel Fuel
- Home Heating Oil
- Hydro-Desulfurized Diesel
- Hydro-Desulfurized Heating Oil
- Light Hydrocracked Distillates

Middle Distillate - Heavy is defined as streams with a 10% distillation temperature between 500 °F and 700°F including such products and intermediates as:

- Cat. Cracker Feed
- Heavy Vacuum Gas Oil
- Heavy Atmospheric Gas Oil
- Heavy Hydrocracked Distillates
- Heavy Cat. Gas Oil
- Coker Gas Oil
- Light Atmospheric Gas Oil
- Light Cat. Gas Oil
- Light Vacuum Gas Oil

The test program was set up for a two-week screening exercise. Two Washington State refineries were visited, one each week, screening 2,548 components. Table 3-2 is a breakdown of the specific process streams on which components were screened and the number of each type of components screened. The streams are listed in order of their 10% distillation temperature which is the temperature at which 10% of the organic would flash off (ASTM Method D-86).

Table 3-2. Component Stream Counts (Washington Refineries)

Refinery's Stream Description	**10% Distillation Temp (Deg F)**	**Number of Components Screened**						
300-499, Middle Distillate, Medium		Fittings	Flange	OEL	Other	Pump	Valve	**Total**
Light Flash Distillate	340	72	17	0	4	2	27	**122**
Heavy/Light Gas Oil	340	29	39	0	2	3	39	**112**
Kerosene	349	40	53	4	2	2	57	**158**
Light Gas Oil	358	31	27	0	1	0	23	**82**
Aeronautical Turbine Fuel	360	186	73	0	18	4	103	**384**
Cracked Heavy Gas Oil	440	7	7	0	0	0	12	**26**
Cracked Hot Heavy Gas Oil	440	5	3	0	1	0	4	**13**
Light Catalytic Gas Oil	464	15	22	2	3	3	24	**69**
Circulating Reflux	470	7	18	0	2	1	12	**40**
Light Diesel	477	28	28	0	2	2	29	**89**
Cracked Very Light Gas Oil	480	12	7	0	1	1	7	**28**
Cracked Very Light	480	21	23	0	2	0	23	**69**
Heavy Gas Oil	492	82	19	0	8	0	54	**163**
	Total =	**535**	**336**	**6**	**46**	**18**	**414**	**1,355**
500 - 699, Middle Distillate, Heavy								
Residual #6	500	51	56	0	7	2	50	**166**
Intermediate Diesel	560	23	15	0	1	1	12	**52**
Heavy Flash Distillate	575	76	60	0	7	3	84	**230**
Extra Heavy Gas Oil	590	36	25	0	1	2	25	**89**
Residual	590	17	26	0	4	2	27	**76**
Light Vacuum Gas Oil	615	28	63	1	7	1	46	**146**
Extra Heavy Flash Distillate	675	28	45	0	6	2	37	**118**
	Total =	**259**	**290**	**1**	**33**	**13**	**281**	**877**
≥ 700, Residual								
Atmospheric Bottoms	700	5	13	0	0	0	12	**30**
Heavy Vacuum Gas Oil	722	21	91	0	7	1	43	**163**
Heavy Vacuum Circulation Reflux	733	2	2	0	0	0	2	**6**
DA Oil	820	35	29	0	4	2	28	**98**
Asphalt	920	5	5	0	1	1	7	**19**
	Total =	**68**	**140**	**0**	**12**	**4**	**92**	**316**

Table 3-3 summarizes the emissions by component type and stream type. The emissions tabulated were computed using the recorded screening values and the correlation equations, zero default values and pegged source values shown in Table 2-1. The raw test data are tabulated in Appendix B. An extensive statistical treatment of these data is presented in Appendix A in which confidence interval and standard error values are tabulated with the emission factor values. The "emission factors" shown in Table 3-3 are the simple average emissions computed for the respective components and stream types.

Table 3-3. Emission Data by Stream Type (Washington Refineries)

Distillate Group & Stream Temp.	Component	Count	Total Emissions (lb/hr)	Emission Factor (lb/hr/comp)
Middle Distillate, Medium (300°- 499° F)				
	Fitting	535	0.00939	1.75E-05
	Flange	336	0.00882	2.62E-05
	OEL	6	0.00013	2.10E-05
	Other	46	0.00041	8.82E-06
	Pump	18	0.01615	8.97E-04
	Valve	414	0.01390	3.36E-05
	Total	1,355	0.0488	3.60E-05
Middle Distillate, Heavy (500° - 699° F)				
	Fitting	259	0.00427	1.65E-05
	Flange	290	0.00379	1.31E-05
	OEL	1	0.00000	4.41E-06
	Other	33	0.00046	1.40E-05
	Pump*	13	0.35580	2.74E-02*
	Valve	281	0.00500	1.78E-05
	Total	877	0.3693	4.20E-04
	* One large leaker, pegged at 100,000 ppm			
Residual (>700° F)				
	Fitting	68	0.00112	1.65E-05
	Flange	140	0.00010	7.18E-07
	Other	12	0.00011	8.82E-06
	Pump	4	0.00265	6.64E-04
	Valve	92	0.00158	1.72E-05
	Total	316	0.0056	1.80E-05
	Grand Total =	2,548	0.42	

Figures 3-1 a-e and 3-2 a-e present the leak rate distributions by component and aggregated for Refineries W1 and W2 respectively. The distributions at the two refineries on a "percent of count" basis are similar, especially if the ≤10 and 11-99 ppmv ranges are combined.

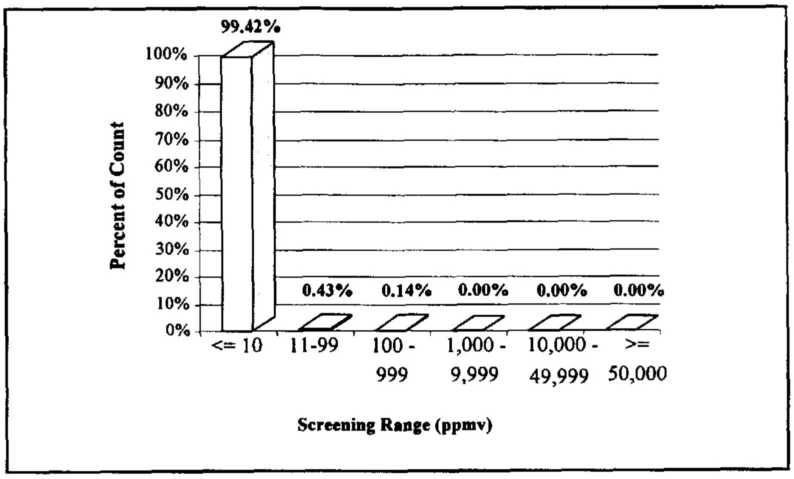

Figure 3-1a. Leak Rate Distributions by Component for Refinery W1 - Fittings

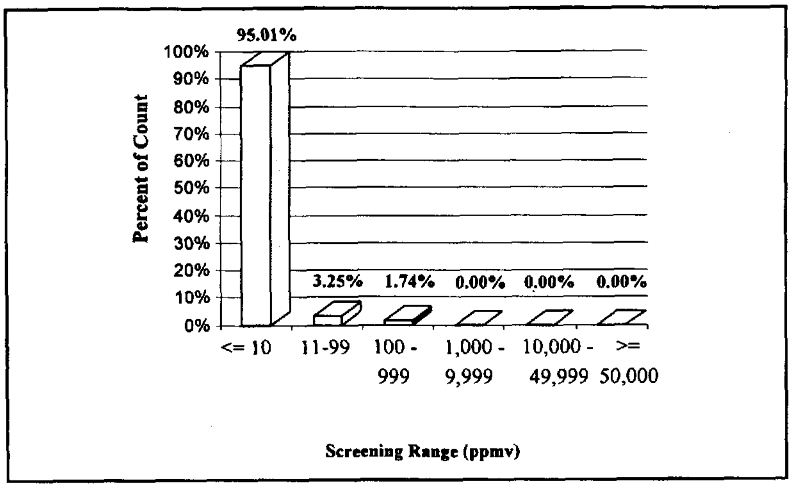

Figure 3-1b. Leak Rate Distributions by Component for Refinery W1 - Flange

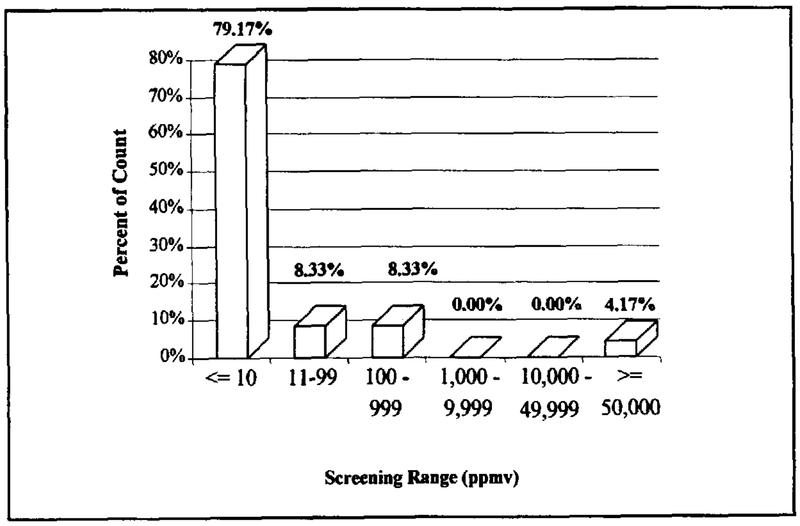

Figure 3-1c. Leak Rate Distributions by Component for Refinery W1 - Pump

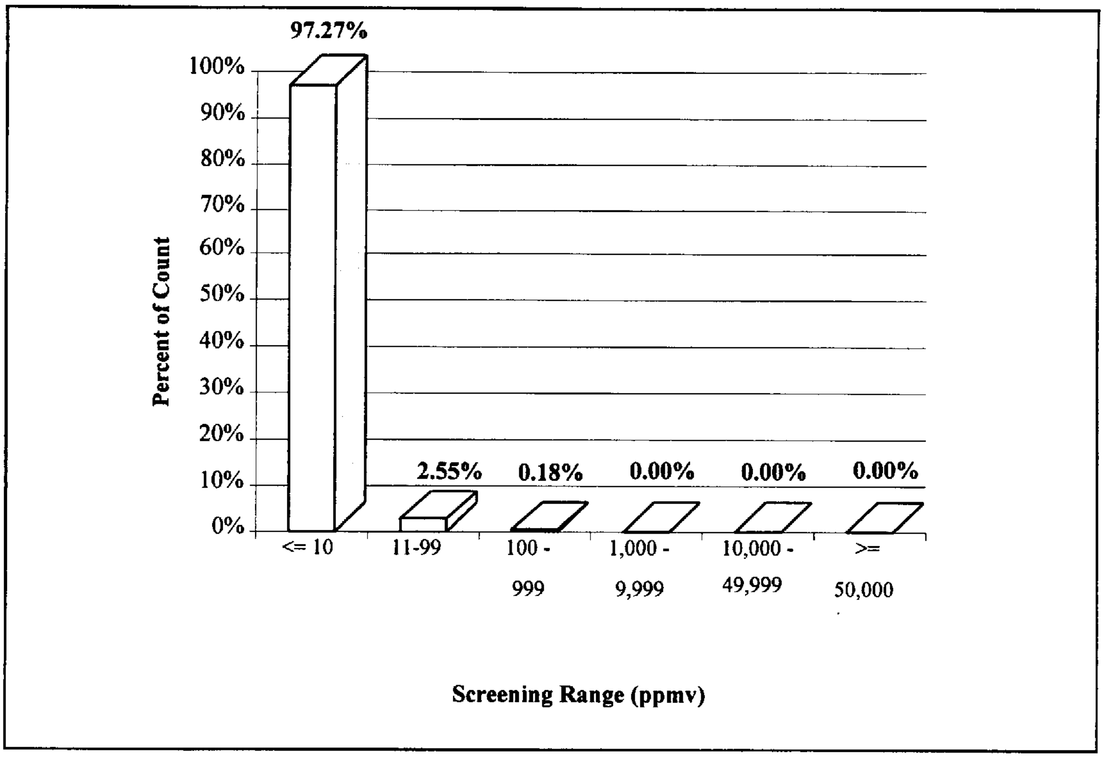

Figure 3-1d. Leak Rate Distributions by Component for Refinery W1 - Valve

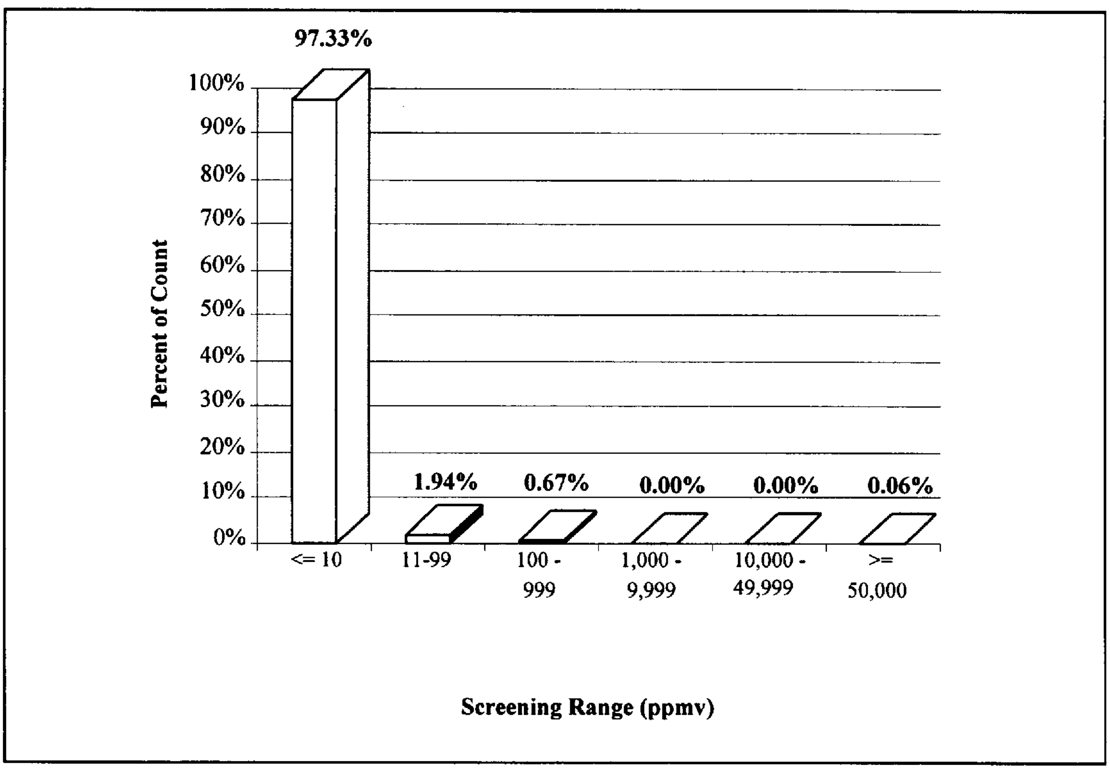

Figure 3-1e. Leak Rate Distributions by Component for Refinery W1 - Aggregate

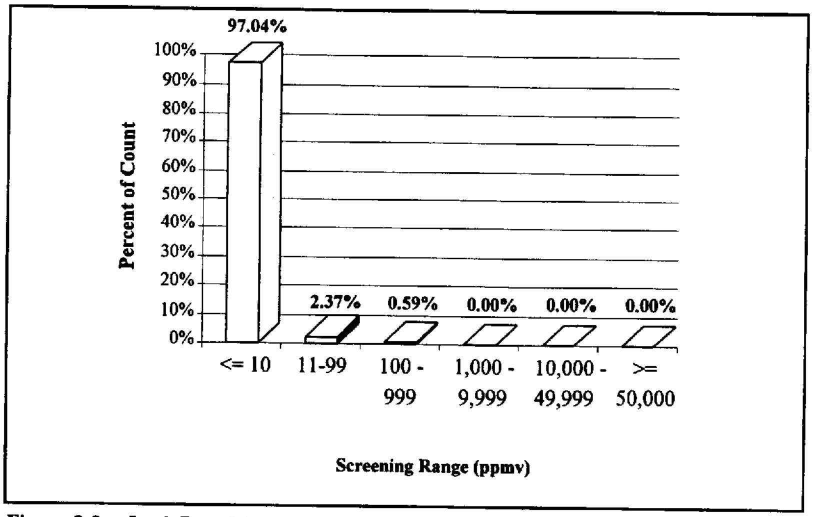

Figure 3-2a. Leak Rate Distributions by Component for Refinery W2 - Fittings

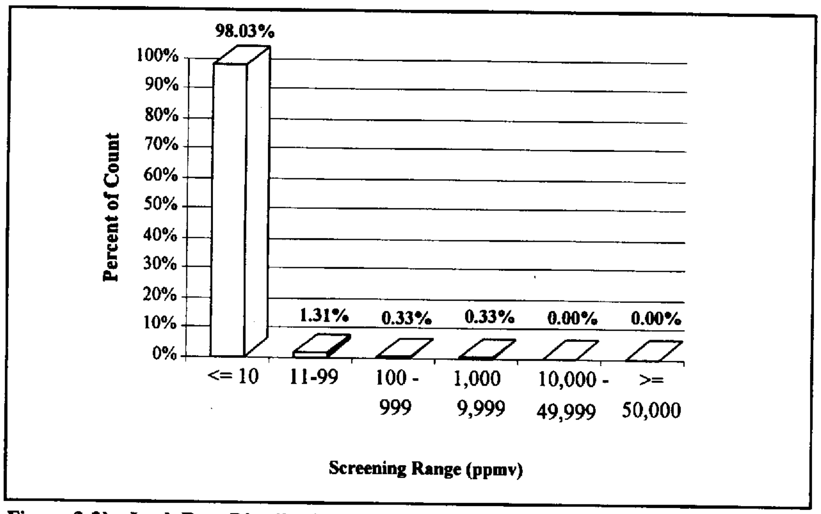

Figure 3-2b. Leak Rate Distributions by Component for Refinery W2 - Flange

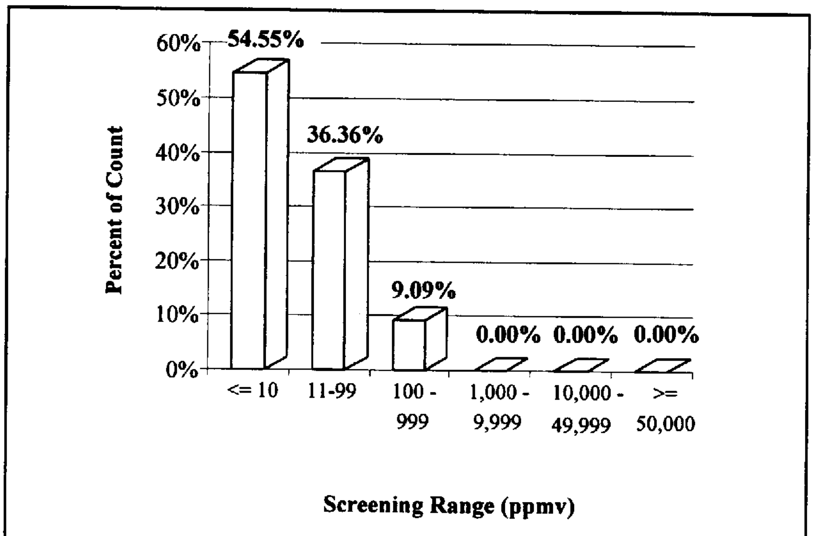

Figure 3-2c. Leak Rate Distributions by Component for Refinery W2 - Pump

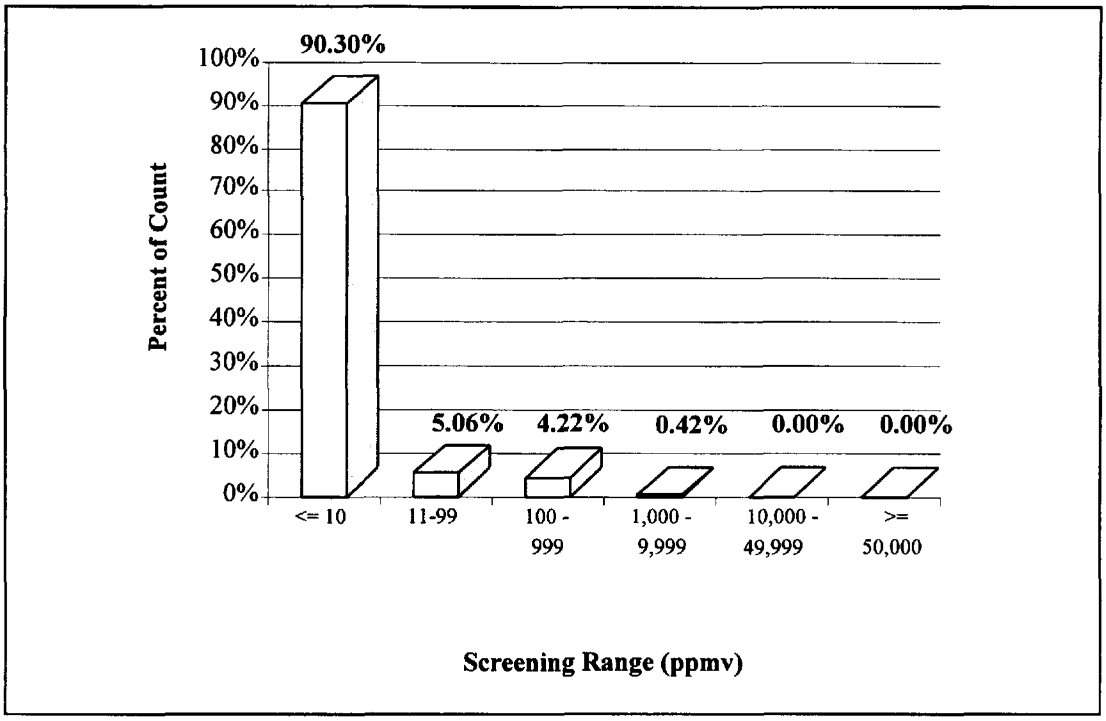

Figure 3-2d. Leak Rate Distributions by Component for Refinery W2 - Valve

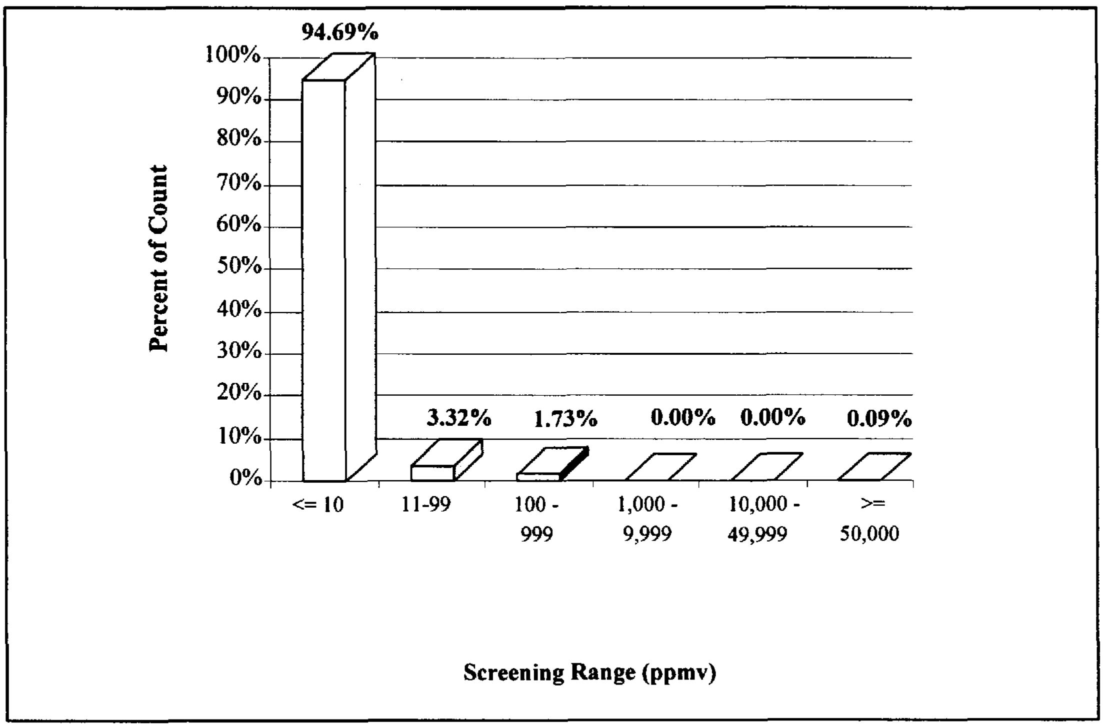

Figure 3-2e. Leak Rate Distributions by Component for Refinery W2 - Aggregate

The emission factor for Heavy Middle Distillate Pump in Refinery W1 (given in Table 3-3) was influenced by one large-leaking pump seal. There is no doubt that this pump seal was leaking greater than 100,000 ppmv screening value. The screening team verified and re-verified the screening value. Interestingly, the stream in which the large leak was discovered is one of the heavier hydrocarbon streams, a material that is discharged at the bottom of the atmospheric still, called "straight run residue," with a 10% distillation temperature of 590°F. However, this pump was handling this hydrocarbon at a temperature of 617°F, a suction pressure of 54 psi, and a discharge pressure of 80 psi. The seal failure was immediately repaired. Nevertheless, the pump seal emission factor for the Washington tests is high because the screening values were recorded prior to repair.

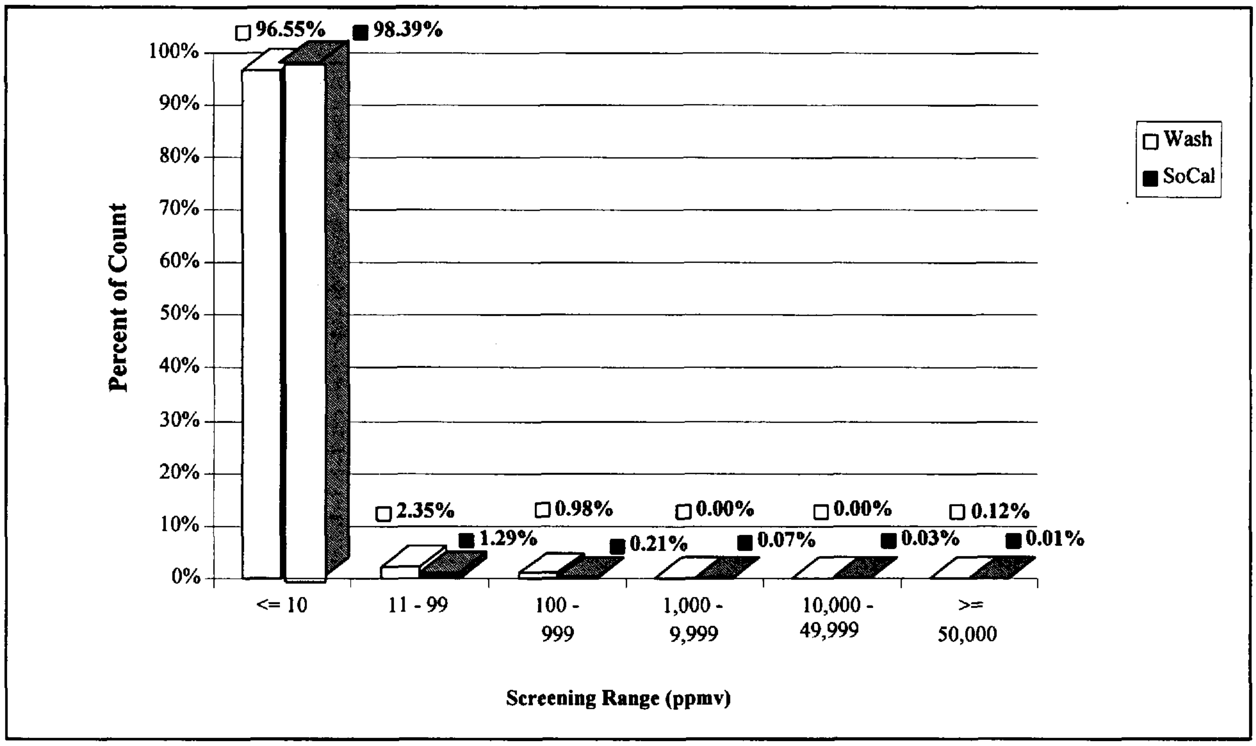

Figure 3-3. Comparison of the Aggregate Leak Rate Distribution for Southern California and Washington Refineries

Table 3-4 summarizes the new screening data by pipeline diameter categories, <2 inches, 2 to 6 inches and >6 inches. No size dependency was noted.

Table 3-4. Emissions Factors by Component Size (Washington Refineries)

Component Size	Component	Count	Total Emissions (lb/hr)	Emission Factor (lb/hr/comp)
< 2"				
	Fittings	847	0.0145	1.91E-05
	Flange	71	0.0005	2.94E-05
	OEL	7	0.0001	3.95E-05
	Other	68	0.0008	1.13E-04
	Valve	441	0.0091	2.96E-05
	Total =	**1,434**	**0.02**	**2.3E-05**
2" - 6"				
	Fittings	15	0.0003	1.96E-05
	Flange	539	0.0047	3.01E-05
	Other	13	0.0001	8.82E-06
	Valve	284	0.0089	3.99E-05
	Total =	**851**	**0.01**	**3.3E-05**
> 6"				
	Flange	156	0.0076	6.96E-05
	Valve	60	0.0025	4.93E-05
	Total =	**216**	**0.01**	**6.4E-05**
No Size Given				
	Other	10	0.0001	8.82E-06
	Pump	35	0.3746	1.07E-02
	Valve	2	0.0000	2.73E-05
	Total =	**47**	**0.37**	**8.0E-03**
	Grand Total =	**2,548**	**0.42**	

Table 3-5 summarizes the new screening data by temperature ranges, <100°F, 100°F to 300°F, 300°F to 500°F, and >500°F. There is not a significant trend here. There is a slight tendency for the emission factors to be higher at higher temperatures. But, as mentioned previously, the higher temperature fluids are also the higher carbon number compounds which are more viscous and less volatile. Therefore, the effects offset each other such that the leak rates are fairly constant.

Table 3-5. Emissions Factors by Temperature (Washington Refineries)

Temperature (Deg F)	Component	Count	Total Emissions (lb/hr)	Emission Factor (lb/hr/comp)
< 100				
	Fittings	187	0.0031	1.66E-05
	Flange	80	0.0006	8.05E-06
	Other	12	0.0001	8.82E-06
	Pump	5	0.0018	3.57E-04
	Valve	105	0.0020	1.89E-05
	Total =	**389**	**0.008**	**2.0E-05**
100 - 299				
	Fittings	274	0.0046	1.67E-05
	Flange	174	0.0005	2.98E-06
	OEL	1	0.0000	4.41E-06
	Other	26	0.0002	8.82E-06
	Pump	5	0.0003	5.53E-04
	Valve	200	0.0039	1.93E-05
	Total =	**680**	**0.009**	**1.4E-05**
300 - 499				
	Fittings	233	0.0042	1.80E-05
	Flange	261	0.0020	7.57E-06
	OEL	6	0.0001	2.10E-05
	Other	32	0.0005	1.42E-05
	Pump	12	0.0045	3.78E-04
	Valve	280	0.0087	3.11E-05
	Total =	**824**	**0.020**	**2.4E-05**
≥ 500				
	Fittings	151	0.0026	1.73E-05
	Flange	227	0.0093	4.11E-05
	Other	18	0.0002	8.82E-06
	Pump	13	0.3680	2.83E-02
	Valve	182	0.0056	3.06E-05
	Total =	**591**	**0.386**	**6.5E-04**
No Temperature Given				
	Fittings	17	0.0003	1.65E-05
	Flange	24	0.0002	1.02E-05
	Other	3	0.0000	8.82E-06
	Valve	20	0.0004	1.75E-05
	Total =	**64**	**0.001**	**1.4E-05**
	Grand Total =	**2,548**	**0.42**	

Based on the statistical analysis in Appendix A, the best estimate of emission factors for the Washington refineries is obtained by averaging the individual measurements for each of the component types. These results are presented in Table 3-6.

Table 3-6. Aggregate Emissions Factors by Component Type (Washington Refineries)

	Washington Data			1980 Data
Component	**Count**	**Total Emissions (lb/hr)**	**Emission Factor (lb/hr/comp)**	**Emission Factor (lb/hr/comp)**
Fittings	862	0.0148	1.71E-05	5.51E-04
Flange	766	0.0127	1.66E-05	5.51E-04
OEL	7	0.0001	1.86E-05	--
Other	91	0.0010	1.07E-05	--
Pump	35	0.3746	1.07E-02	4.63E-02
Valve	787	0.0205	2.60E-05	5.07E-04
Total =	**2,548**	**0.42**		

Section 4

CONCLUSION AND RECOMMENDATION

Based on this program's source testing and data analysis, including the statistical analysis of the data in Appendix A, the primary conclusion is that emission factors for leaks from components in HL service have been determined that are valid for any refinery in the U.S. Two sets of factors derived in Appendix A are presented in Table ES-1 (Page ES-3), one set based on the data available from SoCal refineries and the other based on a combination of the SoCal and Washington data. The Washington factors are lower than Southern California's for all components with the exception of pumps. The higher pump value in Washington was influenced by one pump leaking at a high rate. API recommends the use of the combined set. The new emission factors range from 14% to 35% of the current EPA emission factors (EPA 1993).

The supporting conclusions reached as a result of the statistical analysis follow:

- The SoCal data have a similar distribution of emission rates from quarter to quarter. Therefore, in aggregating screening data from different refineries, where individual refineries have different amounts of data (i.e., 2 quarters, 6 quarters and 7 quarters), the individual-refinery data sets were reduced by averaging repeated measurements for each component.

- The analysis of the Washington State screening data indicates that there is a significant difference in emission factor among component types (e.g., valve, pump). However, the difference in emission factor among the various HL stream types (i.e., medium middle distillate, heavy middle distillate, and heavy residual) are not statistically significant.

- The emission factors for the SoCal refineries and the Washington refineries are statistically similar. (For all components except pump seals the respective emission factors for the Washington refineries are slightly lower than those for the SoCal refineries.) This serves to demonstrate that there should be no significant differences in HL emission factors between areas, with and without LDAR programs, which indicates that the HL emission factors generated by these screening data should be universally applicable to refineries in the U.S.

It was also concluded that for components in HL service the screening values are independent of stream temperature and hydrocarbon composition (as defined by the 10% Distillation

Temperature, ASTM Method D86). At first this may seem odd. The heavy liquid streams range from kerosene to asphalt. Intuitively, kerosene should leak more than asphalt. However, a reasonable explanation of this observed phenomenon is that the heavier hydrocarbons inherently circulate in higher temperature process streams. Therefore, for the medium-weight middle distillate, the heavy-weight middle distillate, and the heavy residual streams, it appears that the viscosity and vapor pressure (properties that affect leakage) have a similar effect on the screening values.

REFERENCE LIST

Radian Corporation, 1992. *Development of Refinery Fugitive Emission Factors for VOCs and Toxics: Review Study Protocol with Phase II Bagging & Speciation Results.* Western States Petroleum Institute (WSPA) and American Petroleum Institute (API). Glendale, C.A. & Washington, D.C.

U.S. Environmental Protection Agency, 1995. Technology Transfer Network (TTN) CHIEF Bulletin Board. Filename: "Leaks_95.wps," (919) 541-5742.

U.S. Environmental Protection Agency, 1993. *Protocol for Equipment Leak Estimates,* Contract 68-d1-0117, for EPA by Radian Corporation, June 1993.

APPENDIX A

Statistical Analysis of Emission Factors for Leaks in Refinery Components in Heavy Liquid Service

INTRODUCTION AND SUMMARY OF RESULTS

This report complements "Development of Emission Factors for Leaks in Refinery Components in Heavy Liquid Service," a study conducted by Hal Taback Company (HTC). API's Statistics Department analyzed existing screening data collected from Southern California and Washington refineries to provide statistical conclusions on several issues, including the following:

- For Southern California refineries, are there quarterly changes in emission rates?
- For Washington State data, are there significant differences in emission rates for various components and different heavy liquid stream types (as categorized in HTC study)?
- Are emission factors for different refineries within Southern California and Washington States comparable?
- Are there significant differences in aggregate emission factors between Southern California and Washington States?
- Is there an appropriate procedure for combining individual refineries' data to obtain aggregate emission factors unaffected by the sizes of individual samples?
- Can confidence intervals be supplied for each of the emission factors computed?
- How do these emission factors compare to those currently recommended by EPA?

The analysis described in this report provided the answers to the main questions listed above using a variety of the advanced statistical modeling methods. It is necessary to emphasize the following general conclusions made in the course of the analysis:

- The analysis of the data collected from Southern California Refineries C1 and C2 has shown that there are no significant differences in the distribution of emission rates by quarter for those refineries (considering all seven quarters of data for Refinery C1, and the last four quarters for refinery C2). Based on this conclusion, those two data sets were reduced by averaging repeated measurements for each component unit over quarters prior to any further analysis.
- The analysis of emission rates for Washington data has provided important information about factors affecting emission rates. The effect of component type has been found significant. The nature of the combined effect of heavy liquid stream type and stream temperature on emission rates has been analyzed, and emission factors for different stream types have been produced. Although we have found emission factors for Medium streams to be slightly higher than emission factors for Heavy/Residual streams, the data collected in the course of

the HTC study does not present enough evidence to consider this difference statistically significant.

- The analysis of the combined Southern California and Washington data has shown that there are no significant differences in emission factors for these two states. This conclusion supports the assumption of no differences in emission factors for states which are in attainment of the National Ambient Air Quality Standards (represented by Washington data) and those that are non-attainment areas and have LDAR (Leak Detection and Repair) programs in effect (Southern California data).

- Pairwise comparisons of refineries within each of Southern California and Washington data sets indicate that emission factors for Washington State refineries are not significantly different while all Southern California refineries show strong differences in average emission rates. Based on these results, a different method is suggested for computing aggregate emission factors for Southern California and combined data sets referred to as a two-step averaging. Aggregate emission factors obtained by this method are shown in Table A-1. Note that for both sets of emission factors presented in Table A-1, the values are significantly lower than HL emission factors currently recommended by EPA.

- The 95% confidence levels were compiled for each emission factor in order to facilitate the comparison between these new HL emission factors and those in EPA's Protocol document.

Table A-1. Suggested Heavy Liquid Service Emission Factors (lb/hr/component)

Component Type	**Emission Factor Southern California Data**	**Emission Factor Combined South. California & Washington Data**	**Emission Factor 1980 EPA**
Fittings	9.49E-05	7.93E-05	5.51E-04
Flange	9.66E-05	7.00E-05	5.51E-04
OEL	--	1.86E-05	--
Other	1.14E-04	6.21E-05	--
Pump	7.63E-03	8.25E-03	4.63E-02
Valve	2.13E-04	1.76E-04	5.07E-04

DATA DESCRIPTION

To address the main points of interest, all the data sets used in the HTC study were obtained and used in the analysis. A brief description of those data sets is presented to highlight certain characteristics of the data.

SOUTHERN CALIFORNIA DATA

As described in HTC's report, the first two refineries' HL screening data (designated refineries C1 and C2) were obtained by HTC directly from the refineries. Refinery C1 supplied 165,852 observations taken over the seven quarters during the period 1992 to 1994. Refinery C2 provided 21,410 screening values collected over the six quarters during the same time period as Refinery C1. The same sets of components in each of the Refineries C1 and C2 were screened in each quarter, producing repeated measurements on the same units over the several quarters. Such a procedure yielded data sets that could not be treated as a collection of independent observations due to the dependencies between consecutive measurements on the same component units. Hence, further analysis was conducted to detect changes in emissions over time for Refineries C1 and C2. Based on the results of this analysis, the data sets for both refineries were summarized first, and then emission factors were computed. The details and results of this analysis are presented in a subsequent section of this Appendix, *Analysis of Emissions by Quarter for Southern California Data.*

The second set of Southern California data collected by HTC was obtained from a previous study and includes the data from two refineries, designated Refineries C3 and C4, taken over the two quarters in 1991. A total of 24,028 screening values were reported: 7,767 for Refinery C3, and 16,261 for Refinery C4.

The data sets provided by HTC for each of the refineries were in summarized form and assumed no repeated measurements on the same component unit during the two consecutive quarters.

WASHINGTON DATA

The second set of data was measured by HTC at two refineries (designated Refineries W1 and W2) located in Washington State. The data set contained 2,548 screening values: 1,795 observations from Refinery W1, and 753 observations from Refinery W2. The screening tests were performed as described in Section 3 of the HTC report, each screening value representing a single independent measurement on a component unit.

As explained in the HTC report, the purpose of this component screening effort was mainly to verify that the Southern California data was representative of all refinery emission factors applicable to components in HL service. On the other hand, advance planing provided an opportunity to collect more information about the components being screened. In addition to component type and screening value, information extracted included type of heavy liquid stream, size of the component, and process parameters (temperature and pressure). This additional information was used in the analysis to identify the main factors affecting emission levels. The analysis is discussed in the section of this Appendix, *Analysis of Emissions by Stream Type for Washington Data.*

All Southern California and Washington data sets analyzed used emission rates computed from screening values provided by HTC (for details about conversion procedure, refer to Section 2 of the HTC report). Based on these emission rates, emission factors (in lb/hr/component) were obtained for each of the data sets by taking simple averages over all available observations for each component type (see Tables A-2 and A-3).

Table A-2. Southern California Refineries - Simple Average Emission Factors

Component Type	Refinery C1		Refinery C2		Refinery C3		Refinery C4	
	Count	EF lb/hr/comp	Count	EF lb/hr/comp	Count	EF lb/hr/comp	Count	EF lb/hr/comp
Fittings	100,482	1.82E-05	14,268	1.84E-05	5,002	1.99E-04	8,310	1.44E-04
Flange	23,370	5.01E-05	1,536	1.43E-04	--	--	--	--
OEL	--	--	--	--	--	--	--	--
Other	12,077	1.13E-04	--	--	--	--	--	--
Pump	787	5.54E-04	72	1.49E-03	58	3.86E-04	58	2.81E-02
Valve	28,265	3.11E-05	5,468	1.55E-04	2,669	3.08E-04	7,468	3.59E-04
PRD	871	1.13E-04	66	8.71E-06	38	9.90E-05	425	1.09E-04

Table A-3. Washington Refineries - Simple Average Emission Factors

Component Type	Refinery W1		Refinery W2	
	Count	EF, lb/hr/comp	Count	EF, lb/hr/comp
Fittings	693	1.68E-05	169	1.87E-05
Flange	461	1.28E-05	305	2.23E-05
OEL	--	--	7	1.86E-05
Other	67	1.14E-05	24	8.82E-06
Pump	24	1.51E-02	11	1.00E-03
Valve	550	1.95E-05	237	4.13E-05

Analysis Of Emissions by Quarter for Southern California Data

The data collected in Southern California from Refineries C1 and C2 deserved special attention because they contained repeated measurements on the same component units over the period of several consecutive quarters. Repeated-measures analysis of variance was used to test whether the differences in emission rates between the quarters are statistically significant. A multivariate model used for both Refineries C1 and C2 was applied to the logarithmic transformation of emission values (used to achieve normality and satisfy the usual linear model assumptions).

Figures A-1 and A-2 show multiple box plots constructed by quarter for Refineries C1 and C2 respectively (in logarithmic scale). A visual examination of Figure A-1 suggests that there are no strong differences in average emissions by quarter for Refinery C1. This suggestion is supported by the results of repeated-measures analysis: the test has shown that the differences between quarters are not statistically significant (p-value for null hypothesis of no quarter effect is 0.61). As Figure A-2 indicates, Refinery C2 does not show such a stable performance. The variability of emission rates and the average level of emissions are changing from quarter to quarter. The results of repeated-measures analysis indicate that the observed difference between quarters is statistically significant (the null hypothesis of no quarter effect is rejected with p-value<=0.01). Pairwise comparisons of emission rates by quarter indicate that the only quarters that differ significantly from the others are the first two (note that those two quarters have a higher spread than the others). The differences in emissions during the last four quarters of the data collection are not statistically significant (at significance level 0.05).

The results of repeated-measures analysis described above not only provide an insight on changes in emissions over time for Refineries C1 and C2, but also suggest a way of dealing with repeated quarterly measurements. Since significant differences in emissions by quarter in Refinery C1 data have not been found, the size of this data set can be significantly reduced without losing any important information by computing the average emission rate over all available quarterly observations for each of the component units. This procedure will generate exactly one emission rate for each unit screened. The size of Refinery C1 data set is thereby reduced from 165,852 to 15,296 observations. Emission factors computed from this reduced data set are shown in Table A-4. For each emission factor, the standard error and 95% confidence interval are computed to allow for comparison to emission factors for original data given in Table A-2. Note that the differences between the two sets of emission factors are minor (original emission factors are within confidence limits for emission factors of the reduced data set).

By applying the above procedure of averaging over quarters before computing emission factors, two major improvements are achieved in the quality of the data set used for the analysis. First, a collection of independent observations is obtained, not a data set with unknown structure of dependencies between quarterly observations on the same units. Second, the size of the reduced data set is now comparable to the size of some other data sets in consideration, which helps to diminish the dominating effect Refinery C1 would have if the original data sets were used to compute aggregate emission factors. Therefore, the reduced Refinery C1 data are more suitable for further analysis of emission rates than the original data set.

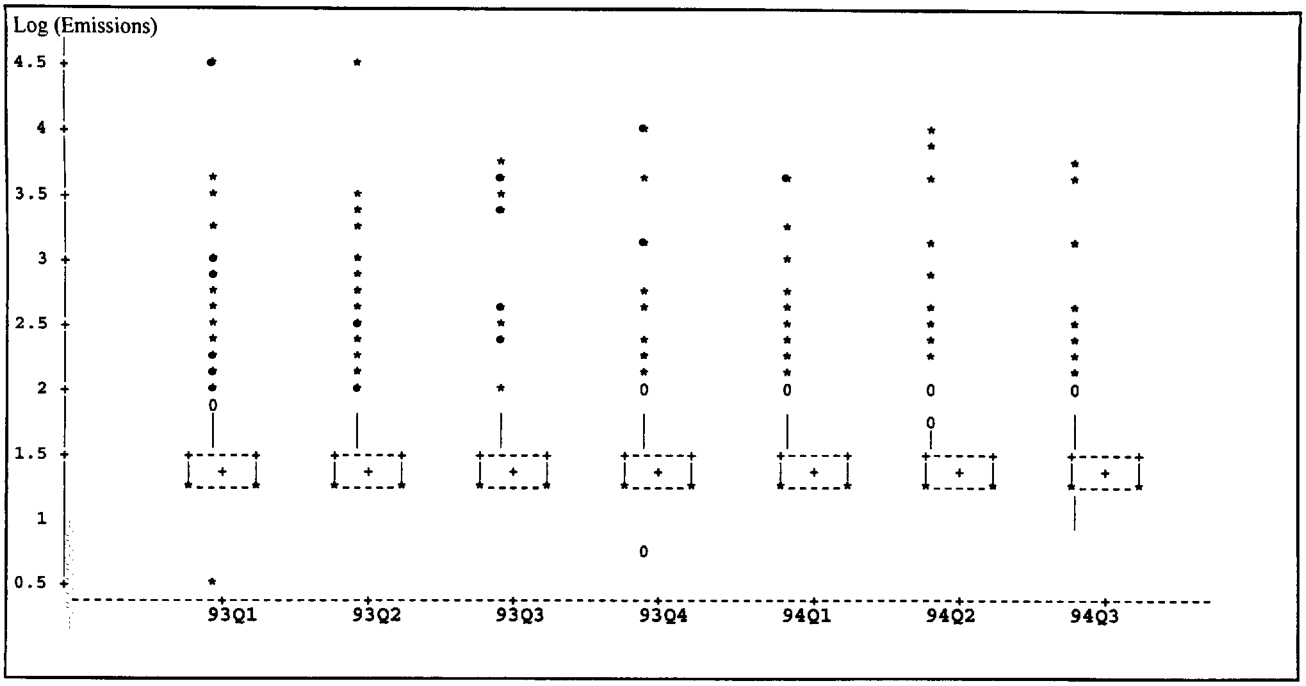

Figure A-1. Distribution of Emissions by Quarter - Refinery C1, Southern California Data

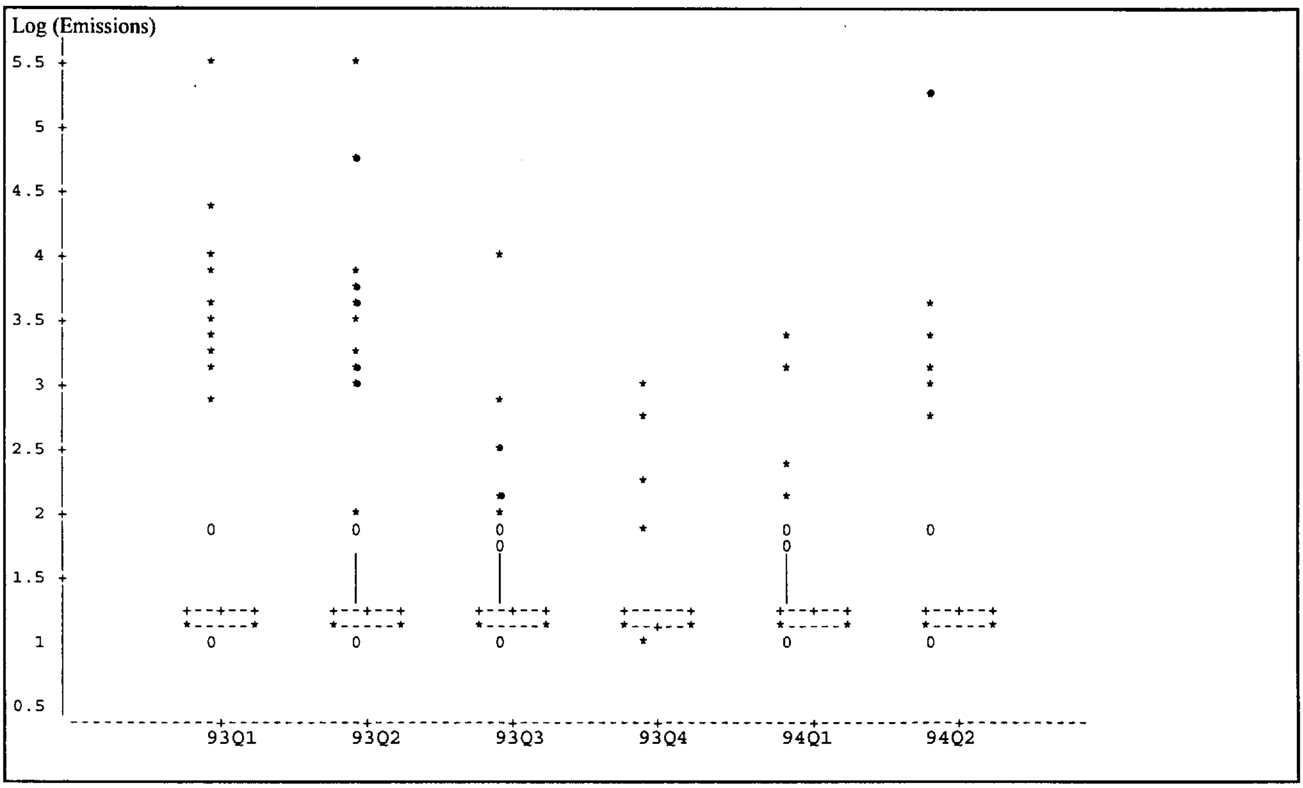

Figure A-2. Distribution of Emissions by Quarter - Refinery C2 Southern California Data

Table A-4. Emission Factors for Reduced Refinery C1 Data (total of 15,296 observations)

Component Type	Count	Emission Factor, lb/hr/component	Standard Error of Emission Factor lb/hr/component	95% Confidence Interval for EF lb/hr/component
Fitting	8,817	1.84E-05	1.13E-07	[1.82E-05, 1.86E-05]
Flange	2,869	5.07E-05	8.00E-07	[4.91E-05, 5.23E-05]
OEL	--	--	--	--
Other	727	1.14E-04	2.71E-07	[1.13E-04, 1.14E-04]
Pump	64	7.61E-04	2.60E-04	[2.42E-04, 1.28E-03]
Valve	2,785	3.25E-05	9.60E-07	[3.06E-05, 3.44E-05]
PRD	34	1.13E-04	0	--

Table A-5 shows emission factors computed after Refinery C2 data is reduced by the same method as described above. Although the overall significance of quarter effect on emission rates for Refinery C2 has been established, the pairwise comparisons between the quarters have shown that only the first two quarters are significantly different from the others. Since emission rates for the last four quarters did not differ significantly, it was decided that the averages over quarters could still be taken for each of the screened component units without causing substantial changes in emission rates. The results in Table A-5 support this point: emission factors for reduced Refinery C2 data are very close to emission factors for original data set shown in Table A-2 (note that all of the original emission factors are within the confidence intervals for emission factors in Table A-5). Hence, further analysis of Refinery C2 data was based on the reduced data set which contains only 4,274 observations (compared to 21,410 observations originally collected).

Table A-5. Emission Factors for Reduced Refinery C2 Data (total of 4,274 observations)*

Component Type	Count	Emission Factor lb/hr/component	Standard Error of Emission Factor, lb/hr/component	95% Confidence Interval for EF lb/hr/component
Fitting	3,032	1.79E-05	5.62E-07	[1.68E-05, 1.90E-05]
Flange	272	1.35E-04	1.13E-04	[0.00*, 3.57E-04]
OEL	--	--	--	--
Other	--	--	--	--
Pump	12	1.49E-03	1.27E-03	[0.00*, 3.97E-03]
Valve	947	1.52E-04	7.81E-05	[0.00*, 3.05E-04]
PRD	11	8.71E-06	0	--

* Confidence intervals are cut off at zero if the lower bound is negative.

Analysis of Stream Type Effect for Washington Data

The data collected from two refineries in Washington State were analyzed to assess the effects of different component and process parameters on emission rates (Southern California data did not have enough information to conduct this type of analysis). Although the influence of heavy liquid stream type on emissions was the main interest, other parameters such as refinery identification, component type and size, stream temperature, and line pressure were also included in the model. The same breakout into categories as in the HTC report was employed for stream type, component size, and stream temperature in our analysis. The breakout for pressure was derived in a similar manner. Also, an artificial effect was introduced which indicates whether the component is actually leaking or not into our modeling process to improve the fit (non-leakers were identified as components with the corresponding zero default emission rate). This effect will be referred to as a leak/non-leak category in the following discussion.

The analysis consisted of several consecutive steps. First, the general linear model containing the factors described above (with interactions) was fit to the data. Then, based on the results, a separate analysis was conducted which was restricted to the subset of leakers that were found to be a main source of variability in the data. This smaller data set (98 observations out of 2,548) was analyzed more closely to verify the conclusions suggested by the analysis of the complete data set. As an additional step, the complete data set was also analyzed as a contingency table to support to the conclusions drawn from the first two steps.

Analysis of Complete Washington Data Set

A linear model with interactions was fit to the logarithmic transformation of the original emission values (the data was transformed in order to satisfy the usual general linear model assumptions). All the factors listed in the beginning of the section were originally included in the model. A stepwise elimination of the insignificant terms yielded the following set of effects included in the final model: component type and size, heavy liquid stream type, stream temperature, leak/non-leak category, and the first-order interactions between the leak/non-leak category and the other factors in the model. All the main effects (component type and size, stream type and temperature, and leak/non-leak category) were found to have a significant effect on emission rates (p-value ≤0.0001) even though the corresponding first-order interactions were present. In particular, the pairwise comparisons for different heavy liquid stream types showed that emission rates for "Medium" streams were significantly different from those for "Heavy" and "Residual" streams (p-value ≤0.0001); on the other hand, no evidence of significant difference in emission rates for Heavy and Residual streams was found (p-value=0.17).

Due to the nature of the logarithmic transformation, all the factors found to be significant in the final model are characterized as having a multiplicative rather than additive effect on emission rates. Note also that one observation with a very high emission rate (component "Pump") was excluded from the modeling process to prevent it from having a substantial effect on the results of this analysis. (However, this value was included in all emission factors computed for data sets containing Washington refineries.)

Although the quality of the fit for the final model described above seemed to be satisfactory (R^2=0.90), it was noticed that the model was not predicting emission rates as might have been expected. A careful examination of the residuals plotted versus predicted values showed that the spread in the residual cloud was created mainly by the observations with emission rates significantly above the default zero levels. To adjust for this, the subset of leakers (identified as components with emission rates above the corresponding default zero level) were extracted and analyzed separately.

Analysis of the Subset of Leakers for Washington Data

The analysis of leakers proceeded in the same direction as the analysis of the complete Washington data set. Since Heavy and Residual stream types did not yield a significant difference in emission rates when modeling the leakers and non-leakers together, it was decided to put the observations from these categories into one stream type subgroup designated Heavy/Residual when analyzing the leakers only. Thus, in the analysis of leakers a comparison is made of emission rates for Medium streams versus emission rates for Heavy/Residual streams.

A linear model similar to the one used for the complete Washington data set was fit to the log transformation of emission rates for the subset of leakers. Here, again, the observation "Pump" with an unusually high emission rate was excluded when constructing the model. The model accounted for 54% of the variation in emission rates (R^2=0.54). The stepwise elimination procedure yielded the following set of significant factors for the subset of leakers: component type, temperature, and the first-order interaction term between stream type and temperature (at significance level 0.05). No effects associated with component size were found to be significant. Although the main effect associated with stream type was not statistically significant (p-value=0.20), this fact alone could not be considered as an indicator of no overall stream type effect in the presence of the interaction. The significance of the interaction between stream type and temperature reflects the joint effect of those two factors which may be different for different combinations of the factor levels.

The nature of this combined effect is illustrated in Figure A-3. The solid line in Figure A-3 shows the changes in emission rates for Medium streams (emission rates are given as averages computed over the set of leakers in the corresponding temperature group regardless of their component type); the dashed line provides the same type of information for Heavy/Residual streams. Note that although some of the categories do not have emission rate estimates (due to unavailability of leakers in the corresponding subgroups), the general pattern is that the combined effect of stream type and temperature is such that emission rates for Medium streams rise with increasing temperature while emission rates for Heavy/Residual streams are high at low temperature levels and low (with a small increase over temperature) at higher levels. The "switch point" on the temperature scale is located somewhere between 100 and 300 degrees Fahrenheit.

Visual examination of Figure A-3 clearly explains how emission rates are affected by changes in temperature and stream type, and why the main effect for stream type (averaged over all interaction subgroups) is not significant: the interchange in stream-temperature effect addressed

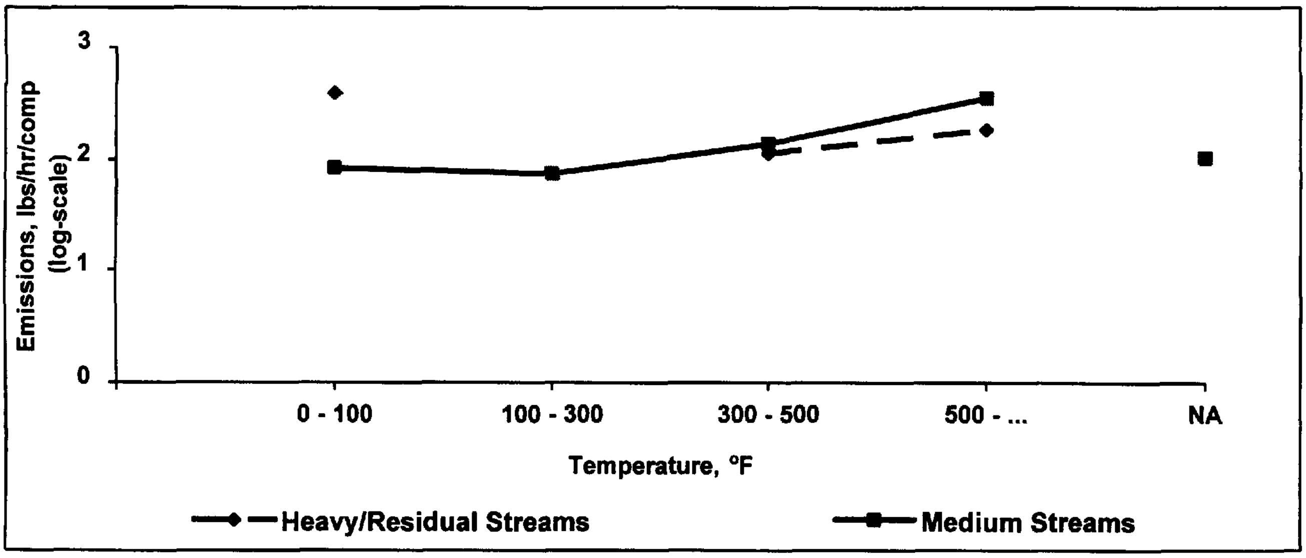

Figure A-3. Illustration of the Combined Effect of Stream Type and Temperature (Subset of Leakers, Washington Data). [Observation with unusually high emission rate (component "Pump") is excluded.]

in the above discussion causes the effects on average to cancel out, yielding an insignificant test result. Similar patterns in combined stream-temperature effect were also observed when emission rates for the two stream types were plotted against temperature for each component type separately.

Therefore, it may be concluded that, in general, emission rates are different for the two stream types being compared (Medium and Heavy/Residual streams) when considering different temperature ranges separately. However, if emission factors are computed across all temperature groups available for any particular component type, the differences between the Medium and Heavy/Residual streams are not significant. Table A-6 shows emission factors for Washington refineries computed for one complete data set (all available observations are included) and by stream type.

Table A-6. Emission Factors for Washington Data by Stream Type

Component	Full Data Set			Medium Streams			Heavy/Residual Streams		
Type	Count	Em Fact lb/hr/comp	Std Error lb/hr/comp	Count	Em Fact lb/hr/comp	Std Error lb/hr/comp	Count	Em Fact lb/hr/comp	Std Error lb/hr/comp
Fittings	862	1.71E-05	2.58E-07	535	1.75E-05	4.14E-07	327	1.65E-05	2.22E-08
Flange	766	1.70E-05	7.31E-06	336	2.62E-05	1.64E-05	430	9.06E-06	2.48E-06
OEL	7	1.86E-05	1.42E-05	6	2.10E-05	1.66E-05	1	4.41E-06	--
Other	91	1.07E-05	1.88E-06	46	8.82E-06	--	45	1.26E-05	3.80E-06
Pump	35	1.07E-02	1.01E-02	18	8.97E-04	4.49E-04	17	2.11E-02	2.07E-02
Valve	787	2.60E-05	2.31E-06	414	3.36E-05	4.35E-06	373	1.76E-05	2.49E-07

Categorical Analysis of Leaks for Washington Data

To provide an alternative to the above analysis based on the generalized linear modeling approach, the Washington data were also analyzed from the categorical point of view. For each of the six component types, a 2x2 contingency table of counts by stream type (Medium or Heavy/Residual) and by leak/non-leak category was constructed, and the tests for association between stream type and leak/non-leak category were performed. (A leaker is any component with a screening value above the zero default value for that component.) The results indicate that the chance of leak occurrence for different stream types depends on component type. Specifically, for Fittings and Valves, the count of leakers is significantly higher for Medium streams than for Heavy/Residual streams (at significance level 0.05), while for OEL, Other, Pumps and Flanges, the differences in the counts of leakers for Medium and Heavy/Residual streams are not statistically significant. Since about two thirds of the total number of observations for Washington data are either Fittings or Valves, it is not surprising that the analysis of contingency table constructed from the complete data set by stream type and leak/non-leak category also yielded the test results indicating the significance of the general association between stream type and leak occurrence after controlling for component type. In other words, even after the differences in component types are taken into account, the chances of leak for Medium streams and Heavy/Residual streams are still significantly different (p-value$\leq$0.0001 for the general test of association). This explains why we are observing slightly higher emission factors for Medium streams for most of the component types (see Table A-6).

Analysis of Aggregate Emission Factors for Southern California and Washington Data

As a final step in the analysis, the Southern California and Washington data (reduced data sets were used for Refineries C1 and C2) were combined and the resulting complete data set was evaluated for differences in emission rates among refineries within each of the states as well as for differences in emissions between the states. To achieve this goal, the generalized linear model for log-transformed emission rates was constructed with the individual refinery factor nested within the state factor (several atypical observations with high emission rates were excluded from the modeling process). Both individual refinery and state factors were considered to be random. This means that available refineries within each of the states were viewed as typical representatives of refinery population for that state (thus, Refinery C1 was considered to be a representative of the population of newer refineries with the full LDAR program while Refineries C3 and C4 represented older refineries with a LDAR program in the beginning stage). Similarly, the test for differences in emission rates between the states was perceived as a comparison between the typical representatives of two populations: states where LDAR (Leak Detection and Repair) programs are required (Southern California data), and states which are in attainment of the National Ambient Air Quality Standards and where LDAR programs are mostly not required with a few exceptions (Washington data). This approach to model interpretation and test results provided a more general understanding of the differences in emission factors among the refineries and between the states.

In addition to state and refinery within-the-state factors, the model also included component type and leak/non-leak category (described in the previous section) along with all the corresponding first-order interactions. The model accounted for 76% of the variation in emission rates for the combined data set (R^2=0.76). Under the assumption that state and refinery factors were random, the tests showed that all the interaction terms in the model were significant (at significance level 0.05). The main effects for refinery within the state factor and component type factor were also found to be significant. However, the model did not yield a significant difference in the main effects for both state factor and leak/non-leak category factor. This means that although we have a significant interaction between state and the other factors in the model, once we average emission rates across each state, the difference is no longer significant. Therefore, there is no need to compute separate emission factors for the states with different LDAR program requirements - we may use either Southern California data alone or combined Southern California and Washington data to compute aggregate emission factors.

Since refinery within-the-state factor was found to be significant in the model described above, several additional tests were performed to identify which refineries within each of the states are significantly different from the others. The test results provided a basis for the final decision on how to combine individual refinery data to obtain the most objective emission factor estimates for each of the states.

Pairwise comparisons between refineries within each of the states showed that Refineries W1 and W2 in Washington State did not have a significant difference in emission rates (p-value=0.8). Thus, emission factors for this state could be computed directly from the complete data set. However, all refineries in Southern California were found to be significantly different (p-value<=0.0001). Hence, for Southern California, we decided to adopt a two-step procedure similar to the one described in the "Analysis of Quarter Effect" section. First, individual emission factors by component type were computed for each refinery in Southern California (original data sets were used for Refineries C3 and C4 while reduced data sets were employed for Refineries C1 and C2). Then, simple arithmetic averages of individual refinery emission factors were taken for each component type to produce aggregate emission factors by component type for Southern California. This procedure seems to be a little more complicated than a straightforward computation, but it has a major advantage of discounting the differences in data set sizes which may have a crucial effect on emission factors for cases where emission patterns for refineries under consideration are not the same. Thus, it is recommend that two-step averaging be used in estimating emission factors over the straightforward calculation.

Table A-7 provides aggregate emission factors for Southern California data obtained by the two-step averaging (all available observations are included). EPA 1980 emission factors are shown for the purpose of comparison. Note that new emission factors obtained from Southern California data are substantially lower than emission factors currently recommended by EPA (none of the EPA's emission factors fall within the confidence limits derived for the Southern California data).

Table A-7. Aggregate Emission Factors for Southern California Refineries*

Component Type	Count	Emission Factor lb/hr/component	95% Confidence Interval for Emission Factor	1980 EPA Emission Factor lb/hr/component
Fittings	25,161	9.49E-05	[5.23E-05, 1.38E-04]	5.51E-04
Flange	3,141	9.66E-05	[0.00* , 2.09E-04]	5.51E-04
OEL	--	--	--	--
Other	727	1.14E-04	[1.13E-04, 1.14E-04]	--
Pump	192	7.63E-03	[0.00* , 2.11E-02]	4.63E-02
Valve	13,869	2.13E-04	[1.24E-04, 3.02E-04]	5.07E-04

* Confidence intervals are cut off at zero if the lower bound is negative.

Table A-8 provides emission factors for Washington State obtained by direct averaging over all available observations for each of the component types (all available observations are included). The 95% confidence intervals are computed in order to facilitate the comparison between these new emission factors an those in EPA's Protocol document.

Table A-8. Aggregate Emission Factors for Washington Refineries*

Component Type	Count	Emission Factor lb/hr/component	95% Confidence Interval for Emission Factor, lb/hr/comp	1980 EPA Emission Factor lb/hr/component
Fittings	862	1.71E-05	[1.66E-05, 1.76E-05]	5.51E-04
Flange	766	1.70E-05	[2.67E-05, 3.13E-05]	5.51E-04
OEL	7	1.86E-05	[0.00* 4.65E-05]	--
Other	91	1.07E-05	[6.94E-06, 1.45E-05]	--
Pump	35	1.07E-02	[0.00* , 3.04E-02]	4.63E-02
Valve	787	2.60E-05	[2.15E-05, 3.05E-05]	5.07E-04

* Confidence intervals are cut off at zero if the lower bound is negative.

Note that emission factors for Washington data (Table A-8) are even lower than those for Southern California data (Table A-7) for all of the component types except "Pump" (which is influenced by one leaking component with a very high emission rate). Lower emission factors for Washington refineries may be explained by the specifics of data collection and combining process. First, note that Southern California data include the results of some older data collection efforts (Refineries C3 and C4) characterized by higher average emission rates, while Washington data were measures only recently and have a low proportion of leaks compared to the older data sets. Second, the two-step procedure adopted for Southern California data assigns equal weights to all of the combined refineries, regardless of the age of an individual refineries' data. This allows the data to be aggregated under different conditions on an equal basis but it may also yield higher emission factors than straightforward averaging due to the influence of the older data sets. In other words, if the emission factors for Southern California are computed using simple averaging by component type, the resulting estimates would be lower and more in agreement with emission factors for Washington data shown in Table A-8. However, EPA may prefer to use emission factors given in Table A-7 for Southern California data because of the advantages associated with the two-step averaging procedure and also because they are more conservative.

Finally, an alternative set of emission factors is suggested based on combined Southern California and Washington data (the results of our analysis indicate that we can combine these data sets because there is no significant difference between the states). Taking in consideration different sizes of individual data sets, we have used the two-step averaging procedure to obtain emission factors for combined data as shown in Table A-9 (Washington refineries provided one aggregate emission factor for each component type; all available observations were included). However, when applied to the combined data, the two-step averaging method assigns equal weights to each of the individual emission factors; thus,Washington refineries have a strong influence on aggregate emission factors regardless of their relatively small data set size. This causes a noticeable decrease in emission factors for some components in Table A-9 when compared to Southern California emission factors in Table A-7. The increase in emission factor for component "Pump" is due to the high emission rate of one observation in the Washington data (the effect of this observation is so strong because of the small data set size).

Table A-9. Emission Factors for Combined Southern California and Washington Data*

Component Type	Count	Emission Factor lb/hr/component	95% Confidence Interval for Emission Factor, lb/hr/component	1980 EPA Emission Factor lb/hr/component
Fittings	26,023	7.93E-05	[4.54E-05, 1.13E-04]	5.51E-04
Flange	3,907	7.00E-05	[0.00*, 1.46E-04]	5.51E-04
OEL	7	1.86E-05	[0.00*, 4.02E-05]	--
Other	818	6.21E-05	[6.03E-05, 6.39E-05]	--
Pump	227	8.25E-03	[0.00*, 1.95E-02]	4.63E-02
Valve	14,656	1.76E-04	[1.05E-04, 2.47E-04]	5.07E-04

* Confidence intervals are cut off at zero if the lower bound is negative.

APPENDIX B

Tabulation of Individual Screenings at Washington Refineries

TABULATION OF INDIVIDUAL SCREENINGS AT WASHINGTON REFINERIES

Refinery	Component	Component Abbreviation	10% Distillation	Service Description	ppm Value	Count	Emissions (lb/hr)
W1	Fittings	TF	590	Extra Heavy Gas Oil	0	4	6.60E-05
W1	Fittings	TC	920	Asphalt	0	5	8.25E-05
W1	Fittings	TC	440	Cracked Hot Heavy Gas Oil	0	5	8.25E-05
W1	Fittings	TC	440	Cracked Heavy Gas Oil	0	7	1.16E-04
W1	Fittings	TC	480	Cracked Very Light Gas Oil	0	12	1.98E-04
W1	Fittings	TC	590	Residual	0	17	2.81E-04
W1	Fittings	TC	480	Cracked Very Light	0	21	3.47E-04
W1	Fittings	TC	340	Heavy/Light Gas Oil	0	27	4.46E-04
W1	Fittings	TC	675	Extra Heavy Flash Distillate	0	28	4.62E-04
W1	Fittings	TC	358	Light Gas Oil	0	29	4.79E-04
W1	Fittings	TC	590	Extra Heavy Gas Oil	0	32	5.28E-04
W1	Fittings	TC	820	DA Oil	0	35	5.78E-04
W1	Fittings	TC	500	Residual # 6	0	50	8.25E-04
W1	Fittings	TC	340	Light Flash Distillate	0	72	1.19E-03
W1	Fittings	TC	575	Heavy Flash Distillate	0	76	1.25E-03
W1	Fittings	TC	492	Heavy Gas Oil	0	82	1.35E-03
W1	Fittings	TC	360	Aeronautical Turbine Fuel	0	185	3.05E-03
W1	Fittings	TC	500	Residual # 6	4	1	9.22E-06
W1	Fittings	TC	358	Light Gas Oil	6	1	1.24E-05
W1	Fittings	TC	358	Light Gas Oil	24	1	3.44E-05
W1	Fittings	TC	340	Heavy/Light Gas Oil	42	1	5.19E-05
W1	Fittings	TC	360	Aeronautical Turbine Fuel	45	1	5.46E-05
W1	Fittings	TC	340	Heavy/Light Gas Oil	142	1	1.27E-04
W1	Flange	FL	440	Cracked Hot Heavy Gas Oil	0	1	7.18E-07
W1	Flange	FL	920	Asphalt	0	5	3.59E-06
W1	Flange	FL	440	Cracked Heavy Gas Oil	0	7	5.03E-06
W1	Flange	FL	480	Cracked Very Light Gas Oil	0	7	5.03E-06
W1	Flange	FL	340	Light Flash Distillate	0	17	1.22E-05
W1	Flange	FL	492	Heavy Gas Oil	0	19	1.36E-05
W1	Flange	FL	590	Extra Heavy Gas Oil	0	20	1.44E-05
W1	Flange	FL	480	Cracked Very Light	0	23	1.65E-05
W1	Flange	FL	590	Residual	0	24	1.72E-05
W1	Flange	FL	358	Light Gas Oil	0	26	1.87E-05

Refinery	Component	Component Abbreviation	10% Distillation	Service Description	ppm Value	Count	Emissions (lb/hr)
W1	Flange	FL	820	DA Oil	0	29	2.08E-05
W1	Flange	FL	340	Heavy/Light Gas Oil	0	32	2.30E-05
W1	Flange	FL	675	Extra Heavy Flash Distillate	0	40	2.87E-05
W1	Flange	FL	500	Residual # 6	0	56	4.02E-05
W1	Flange	FL	575	Heavy Flash Distillate	0	59	4.24E-05
W1	Flange	FL	360	Aeronautical Turbine Fuel	0	71	5.10E-05
W1	Flange	FL	575	Heavy Flash Distillate	7	1	3.84E-05
W1	Flange	FL	590	Residual	10	1	4.94E-05
W1	Flange	FL	675	Extra Heavy Flash Distillate	14	1	6.26E-05
W1	Flange	FL	440	Cracked Hot Heavy Gas Oil	15	1	6.57E-05
W1	Flange	FL	340	Heavy/Light Gas Oil	17	2	1.43E-04
W1	Flange	FL	358	Light Gas Oil	24	1	9.14E-05
W1	Flange	FL	590	Extra Heavy Gas Oil	32	1	1.12E-04
W1	Flange	FL	675	Extra Heavy Flash Distillate	38	1	1.26E-04
W1	Flange	FL	340	Heavy/Light Gas Oil	50	1	1.53E-04
W1	Flange	FL	340	Heavy/Light Gas Oil	52	1	1.57E-04
W1	Flange	FL	440	Cracked Hot Heavy Gas Oil	55	1	1.64E-04
W1	Flange	FL	590	Extra Heavy Gas Oil	62	2	3.56E-04
W1	Flange	FL	360	Aeronautical Turbine Fuel	65	1	1.84E-04
W1	Flange	FL	340	Heavy/Light Gas Oil	80	1	2.13E-04
W1	Flange	FL	590	Extra Heavy Gas Oil	92	1	2.35E-04
W1	Flange	FL	590	Extra Heavy Gas Oil	142	1	3.19E-04
W1	Flange	FL	675	Extra Heavy Flash Distillate	163	1	3.52E-04
W1	Flange	FL	590	Residual	185	1	3.84E-04
W1	Flange	FL	340	Heavy/Light Gas Oil	192	1	3.94E-04
W1	Flange	FL	675	Extra Heavy Flash Distillate	238	1	4.59E-04
W1	Flange	FL	675	Extra Heavy Flash Distillate	240	1	4.61E-04
W1	Flange	FL	340	Heavy/Light Gas Oil	250	1	4.75E-04
W1	Flange	FL	360	Aeronautical Turbine Fuel	341	1	5.91E-04
W1	Other	EX	360	Aeronautical Turbine Fuel	0	1	8.82E-06
W1	Other	M	920	Asphalt	0	1	8.82E-06
W1	Other	M	440	Cracked Hot Heavy Gas Oil	0	1	8.82E-06
W1	Other	M	480	Cracked Very Light Gas Oil	0	1	8.82E-06
W1	Other	MW	820	DA Oil	0	1	8.82E-06
W1	Other	NF	820	DA Oil	0	1	8.82E-06
W1	Other	M	590	Extra Heavy Gas Oil	0	1	8.82E-06

Refinery	Component	Component Abbreviation	10% Distillation	Service Description	ppm Value	Count	Emissions (lb/hr)
W1	Other	M	358	Light Gas Oil	0	1	8.82E-06
W1	Other	EX	500	Residual # 6	0	1	8.82E-06
W1	Other	M	480	Cracked Very Light	0	2	1.76E-05
W1	Other	M	820	DA Oil	0	2	1.76E-05
W1	Other	D	675	Extra Heavy Flash Distillate	0	2	1.76E-05
W1	Other	M	340	Heavy/Light Gas Oil	0	2	1.76E-05
W1	Other	M	675	Extra Heavy Flash Distillate	0	4	3.53E-05
W1	Other	M	340	Light Flash Distillate	0	4	3.53E-05
W1	Other	M	590	Residual	0	4	3.53E-05
W1	Other	M	575	Heavy Flash Distillate	0	6	5.29E-05
W1	Other	M	500	Residual # 6	0	6	5.29E-05
W1	Other	M	492	Heavy Gas Oil	0	8	7.06E-05
W1	Other	M	360	Aeronautical Turbine Fuel	0	17	1.50E-04
W1	Other	M	575	Heavy Flash Distillate	22	1	1.80E-04
W1	Pump	P	480	Cracked Very Light Gas Oil	0	1	5.53E-05
W1	Pump	P	820	DA Oil	0	1	5.53E-05
W1	Pump	P	340	Light Flash Distillate	0	1	5.53E-05
W1	Pump	P	590	Residual	0	1	5.53E-05
W1	Pump	P	675	Extra Heavy Flash Distillate	0	2	1.11E-04
W1	Pump	P	340	Heavy/Light Gas Oil	0	2	1.11E-04
W1	Pump	P	500	Residual # 6	0	2	1.11E-04
W1	Pump	P	575	Heavy Flash Distillate	0	3	1.66E-04
W1	Pump	P	360	Aeronautical Turbine Fuel	0	4	2.21E-04
W1	Pump	P	590	Extra Heavy Gas Oil	7	1	3.47E-04
W1	Pump	P	920	Asphalt	10	1	4.32E-04
W1	Pump	P	340	Light Flash Distillate	13	1	5.07E-04
W1	Pump	P	590	Extra Heavy Gas Oil	47	1	1.11E-03
W1	Pump	P	820	DA Oil	135	1	2.11E-03
W1	Pump	P	340	Heavy/Light Gas Oil	580	1	5.14E-03
W1	Pump	P	590	Residual	99,988	1	3.53E-01
W1	Valve	V	440	Cracked Hot Heavy Gas Oil	0	4	6.88E-05
W1	Valve	V	920	Asphalt	0	7	1.20E-04
W1	Valve	V	480	Cracked Very Light Gas Oil	0	7	1.20E-04
W1	Valve	V	440	Cracked Heavy Gas Oil	0	12	2.06E-04
W1	Valve	V	358	Light Gas Oil	0	18	3.10E-04
W1	Valve	V	480	Cracked Very Light	0	23	3.96E-04

Refinery	Component	Component Abbreviation	10% Distillation	Service Description	ppm Value	Count	Emissions (lb/hr)
W1	Valve	V	590	Extra Heavy Gas Oil	0	24	4.13E-04
W1	Valve	V	340	Light Flash Distillate	0	27	4.64E-04
W1	Valve	V	590	Residual	0	27	4.64E-04
W1	Valve	V	820	DA Oil	0	28	4.82E-04
W1	Valve	V	340	Heavy/Light Gas Oil	0	29	4.99E-04
W1	Valve	V	675	Extra Heavy Flash Distillate	0	35	6.02E-04
W1	Valve	V	500	Residual # 6	0	49	8.43E-04
W1	Valve	V	492	Heavy Gas Oil	0	54	9.29E-04
W1	Valve	V	575	Heavy Flash Distillate	0	84	1.44E-03
W1	Valve	V	360	Aeronautical Turbine Fuel	0	102	1.75E-03
W1	Valve	V	358	Light Gas Oil	4	1	1.41E-05
W1	Valve	V	500	Residual # 6	8	1	2.37E-05
W1	Valve	V	360	Aeronautical Turbine Fuel	10	1	2.80E-05
W1	Valve	V	358	Light Gas Oil	10	2	5.61E-05
W1	Valve	V	340	Heavy/Light Gas Oil	12	1	3.21E-05
W1	Valve	V	675	Extra Heavy Flash Distillate	20	1	4.70E-05
W1	Valve	V	340	Heavy/Light Gas Oil	22	2	1.01E-04
W1	Valve	V	358	Light Gas Oil	24	1	5.39E-05
W1	Valve	V	675	Extra Heavy Flash Distillate	25	1	5.55E-05
W1	Valve	V	340	Heavy/Light Gas Oil	32	1	6.67E-05
W1	Valve	V	340	Heavy/Light Gas Oil	35	1	7.14E-05
W1	Valve	V	590	Extra Heavy Gas Oil	52	1	9.59E-05
W1	Valve	V	340	Heavy/Light Gas Oil	52	1	9.59E-05
W1	Valve	V	340	Heavy/Light Gas Oil	55	1	1.00E-04
W1	Valve	V	340	Heavy/Light Gas Oil	82	1	1.35E-04
W1	Valve	V	340	Heavy/Light Gas Oil	85	1	1.38E-04
W1	Valve	V	358	Light Gas Oil	94	1	1.49E-04
W1	Valve	V	340	Heavy/Light Gas Oil	270	1	3.28E-04
W2	Fittings	TC	733	Heavy Vacuum W1irc. Reflux	0	2	3.30E-05
W2	Fittings	TC	700	Atmospheric Bottoms	0	5	8.25E-05
W2	Fittings	TC	470	Circulating Reflux	0	7	1.16E-04
W2	Fittings	TC	464	Light Catalytic Gas Oil	0	15	2.48E-04
W2	Fittings	TC	722	Heavy Vacuum Gas Oil	0	21	3.47E-04
W2	Fittings	TC	560	Intermediate Diesel	0	23	3.80E-04
W2	Fittings	TC	477	Light Diesel	0	27	4.46E-04
W2	Fittings	TC	615	Light Vacuum Gas Oil	0	28	4.62E-04

Refinery	Component	Component Abbreviation	10% Distillation	Service Description	ppm Value	Count	Emissions (lb/hr)
W2	Fittings	TC	349	Kerosene	0	36	5.94E-04
W2	Fittings	TC	477	Light Diesel	20	1	3.01E-05
W2	Fittings	TC	349	Kerosene	75	1	7.95E-05
W2	Fittings	TC	349	Kerosene	85	1	8.72E-05
W2	Fittings	TC	349	Kerosene	95	1	9.46E-05
W2	Fittings	TC	349	Kerosene	185	1	1.54E-04
W2	Flange	FL	733	Heavy Vacuum Circ. Reflux	0	2	1.44E-06
W2	Flange	FL	700	Atmospheric Bottoms	0	13	9.33E-06
W2	Flange	FL	560	Intermediate Diesel	0	14	1.01E-05
W2	Flange	FL	470	Circulating Reflux	0	17	1.22E-05
W2	Flange	FL	464	Light Catalytic Gas Oil	0	22	1.58E-05
W2	Flange	FL	477	Light Diesel	0	27	1.94E-05
W2	Flange	FL	349	Kerosene	0	50	3.59E-05
W2	Flange	FL	615	Light Vacuum Gas Oil	0	60	4.31E-05
W2	Flange	FL	722	Heavy Vacuum Gas Oil	0	91	6.53E-05
W2	Flange	FL	615	Light Vacuum Gas Oil	8	1	4.22E-05
W2	Flange	FL	615	Light Vacuum Gas Oil	9	1	4.59E-05
W2	Flange	FL	477	Light Diesel	10	1	4.94E-05
W2	Flange	FL	349	Kerosene	25	1	9.41E-05
W2	Flange	FL	615	Light Vacuum Gas Oil	30	1	1.07E-04
W2	Flange	FL	349	Kerosene	50	1	1.53E-04
W2	Flange	FL	349	Kerosene	95	1	2.41E-04
W2	Flange	FL	560	Intermediate Diesel	230	1	4.48E-04
W2	Flange	FL	470	Circulating Reflux	7,985	1	5.42E-03
W2	OEL	OEL	615	Light Vacuum Gas Oil	0	1	4.41E-06
W2	OEL	OEL	464	Light Catalytic Gas Oil	0	2	8.82E-06
W2	OEL	OEL	349	Kerosene	0	3	1.32E-05
W2	OEL	OEL	349	Kerosene	80	1	1.04E-04
W2	Other	M	560	Intermediate Diesel	0	1	8.82E-06
W2	Other	M	349	Kerosene	0	1	8.82E-06
W2	Other	EX	349	Kerosene	0	1	8.82E-06
W2	Other	MW	464	Light Catalytic Gas Oil	0	1	8.82E-06
W2	Other	MW	615	Light Vacuum Gas Oil	0	1	8.82E-06
W2	Other	S	615	Light Vacuum Gas Oil	0	1	8.82E-06
W2	Other	M	470	Circulating Reflux	0	2	1.76E-05
W2	Other	M	464	Light Catalytic Gas Oil	0	2	1.76E-05

Refinery	Component	Component Abbreviation	10% Distillation	Service Description	ppm Value	Count	Emissions (lb/hr)
W2	Other	M	477	Light Diesel	0	2	1.76E-05
W2	Other	ST	615	Light Vacuum Gas Oil	0	2	1.76E-05
W2	Other	M	722	Heavy Vacuum Gas Oil	0	3	2.65E-05
W2	Other	M	615	Light Vacuum Gas Oil	0	3	2.65E-05
W2	Other	EX	722	Heavy Vacuum Gas Oil	0	4	3.53E-05
W2	Pump	P	470	Circulating Reflux	0	1	5.53E-05
W2	Pump	P	722	Heavy Vacuum Gas Oil	0	1	5.53E-05
W2	Pump	P	349	Kerosene	0	1	5.53E-05
W2	Pump	P	615	Light Vacuum Gas Oil	0	1	5.53E-05
W2	Pump	P	464	Light Catalytic Gas Oil	0	2	1.11E-04
W2	Pump	P	464	Light Catalytic Gas Oil	27	1	7.91E-04
W2	Pump	P	560	Intermediate Diesel	30	1	8.44E-04
W2	Pump	P	349	Kerosene	30	1	8.44E-04
W2	Pump	P	477	Light Diesel	70	1	1.42E-03
W2	Pump	P	477	Light Diesel	915	1	6.79E-03
W2	Valve	V	733	Heavy Vacuum Circ. Reflux	0	2	3.44E-05
W2	Valve	V	470	Circulating Reflux	0	7	1.20E-04
W2	Valve	V	700	Atmospheric Bottoms	0	12	2.06E-04
W2	Valve	V	560	Intermediate Diesel	0	12	2.06E-04
W2	Valve	V	464	Light Catalytic Gas Oil	0	24	4.13E-04
W2	Valve	V	477	Light Diesel	0	28	4.82E-04
W2	Valve	V	349	Kerosene	0	40	6.88E-04
W2	Valve	V	722	Heavy Vacuum Gas Oil	0	43	7.40E-04
W2	Valve	V	615	Light Vacuum Gas Oil	0	45	7.74E-04
W2	Valve	V	615	Light Vacuum Gas Oil	10	1	2.80E-05
W2	Valve	V	349	Kerosene	15	1	3.79E-05
W2	Valve	V	349	Kerosene	20	3	1.41E-04
W2	Valve	V	470	Circulating Reflux	30	1	6.36E-05
W2	Valve	V	470	Circulating Reflux	45	1	8.61E-05
W2	Valve	V	349	Kerosene	45	1	8.61E-05
W2	Valve	V	349	Kerosene	55	1	1.00E-04
W2	Valve	V	470	Circulating Reflux	65	1	1.13E-04
W2	Valve	V	349	Kerosene	65	1	1.13E-04
W2	Valve	V	349	Kerosene	70	1	1.20E-04
W2	Valve	V	349	Kerosene	75	1	1.26E-04
W2	Valve	V	349	Kerosene	120	1	1.79E-04

Refinery	Component	Component Abbreviation	10% Distillation	Service Description	ppm Value	Count	Emissions (lb/hr)
W2	Valve	V	349	Kerosene	160	1	2.22E-04
W2	Valve	V	349	Kerosene	175	1	2.37E-04
W2	Valve	V	349	Kerosene	220	1	2.81E-04
W2	Valve	V	349	Kerosene	270	1	3.28E-04
W2	Valve	V	477	Light Diesel	270	1	3.28E-04
W2	Valve	V	349	Kerosene	365	1	4.10E-04
W2	Valve	V	349	Kerosene	420	1	4.56E-04
W2	Valve	V	470	Circulating Reflux	720	1	6.81E-04
W2	Valve	V	470	Circulating Reflux	915	1	8.14E-04
W2	Valve	V	349	Kerosene	1,475	1	1.16E-03

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