

Fugitive Hydrocarbon Emissions from Oil and Gas Production Operations

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PREFACE

This report presents final results of an API/GRI study entitled "Fugitive Hydrocarbon Emissions from Oil and Gas Production Operations". The data collection efforts and development of correlation equations and emission factors for fugitive hydrocarbon emissions from oil and gas production operations described in this report include onshore light crude facilities, onshore heavy crude facilities, onshore gas production facilities, and offshore oil and gas facilities. A gas processing plant correlation equation is included, but emission factors for gas processing plants are not. Emission factors for gas processing plants will be determined in 1994 and reported in a separate report after more field data are collected in a joint research effort with the EPA. The statistical analysis of the data gathered in this study was conducted in accordance with the US EPA Protocol for Equipment Leak Emission Estimates (EPA-453/R-93-026, June 1993) to facilitate acceptance by the EPA. The American Petroleum Institute does not necessarily endorse the EPA protocol as the best method for analyzing the data in this study. There may be other methods of statistical analysis that are more appropriate. In this study, as in the EPA protocol, the common convention of reporting emission factors to three significant figures has been followed, even though it may not be warranted given the inherent variation in the precision and accuracy of emissions measurements.

ABSTRACT

In 1980, the American Petroleum Institute published emission factors for fugitive hydrocarbon emissions from onshore and offshore petroleum production sites. The new emission factors developed from this joint study by API and the Gas Research Institute replace the existing 1980 API factors. More than 180,000 components were screened using EPA Method 21 guidelines and over 700 leaks were speciated to determine new emission rates of total hydrocarbons, volatile organic compounds, and individual air toxics (i.e., benzene, toluene, ethyl benzene, and xylenes).

The new study has also produced emission correlation equations that can be used to predict mass emission rates from individual instrument screening values. These equations allow operators to more accurately quantify actual emissions from their site rather than relying on generalized emission factors. This greatly improves assessment of control technologies and selection of equipment to lower fugitive hydrocarbon emissions. As the new leak definition imposed by the Clean Air Act Amendments of 1990 becomes effective, results of this study will be indispensable to operators.

Results of the study are summarized in easy-to-read graphics and easy-to-use factors. A workbook presented at the end of the report allows site operators to tailor the new factors and equations to their individual use.

TABLE OF CONTENTS

<u>SECTION</u>	<u>PAGE</u>
EXECUTIVE SUMMARY	ES-1
1. STUDY METHODOLOGY.....	1-1
INTRODUCTION.....	1-1
Objectives.....	1-1
Scope.....	1-1
DESCRIPTION OF METHODOLOGY.....	1-2
Study Site Selection.....	1-3
Screening Procedures.....	1-4
Bagging Procedures	1-6
Laboratory Procedures.....	1-8
Quality Assurance/Quality Control Procedures.....	1-8
DATA MANAGEMENT.....	1-9
Development of Correlation Equations.....	1-9
Development of Emission Factors.....	1-10
2. ONSHORE RESULTS AND ANALYSIS.....	2-1
DATA COLLECTION.....	2-1
QUALITY ASSURANCE/QUALITY CONTROL.....	2-5
CORRELATION EQUATIONS.....	2-16
EMISSION FACTORS.....	2-21
Average Emission Factors.....	2-21
Leak/No Leak Emission Factors.....	2-22
Stratified Emission Factors.....	2-22
SPECIATION OF EMISSIONS.....	2-22
REGIONAL DIFFERENCES IN FUGITIVE EMISSIONS.....	2-36
CONTROL EFFICIENCY OF INSPECTION AND MAINTENANCE PROGRAMS....	2-36
3. OFFSHORE RESULTS AND ANALYSIS.....	3-1
DATA COLLECTION.....	3-1
QUALITY ASSURANCE/QUALITY CONTROL.....	3-4
CORRELATION EQUATIONS.....	3-5
EMISSION FACTORS.....	3-7
Average Emission Factors.....	3-7
Leak/No Leak Emission Factors.....	3-7
Stratified Emission Factors.....	3-7
SPECIATION OF EMISSIONS.....	3-8

TABLE OF CONTENTS (Continued)

<u>SECTION</u>	<u>PAGE</u>
3. OFFSHORE RESULTS AND ANALYSIS (Continued)	
REGIONAL DIFFERENCES IN FUGITIVE EMISSIONS	3-14
CONTROL EFFICIENCY OF INSPECTION AND MAINTENANCE PROGRAMS....	3-15
FUGITIVE EMISSIONS WORKBOOK.....	W-1

LIST OF APPENDICES

APPENDIX A STATISTICAL ANALYSIS OF DATA	A-1
APPENDIX B: FIELD INVENTORY SHEET DATA	B-1
APPENDIX C EMITTER DATA.....	C-1
APPENDIX D NONAROMATIC SPECIATION DATA.....	D-1
APPENDIX E AROMATIC SPECIATION DATA.....	E-1

**Documents**

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LIST OF TABLES

<u>TABLE</u>	<u>PAGE</u>
ES-1 Number of Components Screened, Emitters Found, and Samples Collected and Analyzed during API/GRI Study	ES-2
ES-2 Correlation Equations	ES-5
ES-3 Default Zero THC Emission Factors	ES-5
ES-4 Average THC Emission Factors (Overall)	ES-6
ES-5 Average THC Emission Factors (Component Specific).....	ES-6
ES-6 Leak/No Leak THC Emission Factors.....	ES-6
ES-7 Stratified THC Emission Factors.....	ES-7
ES-8 Speciated Hydrocarbon Factors.....	ES-7
1-1 Sites Included in the 1993 API/GRI Study	1-4
2-1 Components Screened and Emitters Found at Onshore Sites	2-2
2-2 Onshore Emitters by Screening Range	2-2
2-3 Contribution of Each Screening Range to Total Emissions	2-4
2-4 First and Second Analyses for Nonaromatic Hydrocarbons.....	2-6
2-5 First and Second Analyses for Aromatic Hydrocarbons	2-12
2-6 Correlation of Repeated Laboratory Analyses	2-15
2-7 Correlation Equations	2-17
2-8 Default Zero THC Emission Factors	2-21
2-9 Average THC Emission Factors (Overall)	2-21
2-10 Average THC Emission Factors (Component specific)	2-21
2-11 Leak/No-Leak THC Emission Factors	2-22
2-12 Stratified THC Emission Factors.....	2-22
2-13 Weight Fraction of Emissions by Number of Carbons.....	2-36
2-14 Average Emission Rate of Components with ISVs of $\geq 100,000$ ppmv (By region)	2-36
3-1 Components Screened and Emitters Found at Offshore Platforms.....	3-1
3-2 Offshore Emitters by Screening Range	3-2
3-3 Contribution of Each Screening Range to Total Emissions	3-4
3-4 Correlation Equations	3-5
3-5 Default Zero THC Emission Factors	3-5
3-6 Average THC Emission Factors (Overall)	3-7
3-7 Average THC Emission Factors (Component specific)	3-7
3-8 Leak/No-Leak THC Emission Factors	3-7
3-9 Stratified THC Emission Factors.....	3-8



Documents

Document Sharing Hub

LIST OF TABLES (Continued)

<u>SECTION</u>	<u>PAGE</u>
3-10 Weight Fraction of Emissions by Number of Carbons.....	3-8
3-11 Number of Components Installed on Pacific OCS Platforms Monitored by the MMS, and the Average Leak Rates.....	3-14
3-12 Fugitive Hydrocarbon Emissions Predicted by MMS and API/GRI Correlation Equations.....	3-14

LIST OF FIGURES

<u>FIGURE</u>	<u>PAGE</u>
1-1 1993 API/GRI Study Sites.....	1-3
2-1 Distribution of Onshore Emitters.....	2-3
2-2 Percent of Total Emission by Range.....	2-3
2-3 Comparison of Repeat Analyses at Laboratory (C1)	2-9
2-4 Comparison of Repeat Analyses at Laboratory (C2)	2-9
2-5 Comparison of Repeat Analyses at Laboratory (C3)	2-10
2-6 Comparison of Repeat Analyses at Laboratory (C4)	2-10
2-7 Comparison of Repeat Analyses at Laboratory (C5)	2-11
2-8 Comparison of Repeat Analyses at Laboratory (C6+)	2-11
2-9 Comparison of Repeat Analyses at Laboratory (Benzene).....	2-13
2-10 Comparison of Repeat Analyses at Laboratory (Toluene)	2-13
2-11 Comparison of Repeat Analyses at Laboratory (Ethyl-Benzene).....	2-14
2-12 Comparison of Repeat Analyses at Laboratory (m+p Xylene).....	2-14
2-13 Comparison of Repeat Analyses at Laboratory (o Xylene).....	2-15
2-14 Comparison of Onshore Sample Bags as Collected and as Analyzed	2-16
2-15 Light Crude Production Correlation (CN, VL, OEL).....	2-18
2-16 Light Crude Production Correlation (Others).....	2-18
2-17 Heavy Crude Production Correlation (CN, VL, OEL, Others).....	2-19
2-18 Natural Gas Production Correlation (CN, OEL)	2-19
2-19 Natural Gas Production Correlation (VL, Others).....	2-20
2-20 Natural Gas Processing Correlation (CN, VL, OEL, Others).....	2-20
2-21 Weight Percent Hydrocarbons in Samples (Light Crude #1)	2-24
2-22 Weight Percent Hydrocarbons in Samples (Light Crude #2)	2-25
2-23 Weight Percent Hydrocarbons in Samples (Light Crude #3)	2-26
2-24 Weight Percent Hydrocarbons in Samples (Light Crude #4)	2-27
2-25 Weight Percent Hydrocarbons in Samples (Heavy Crude #5, 6, 7, & 8).....	2-28
2-26 Weight Percent Hydrocarbons in Samples (Gas Production #9)	2-29
2-27 Weight Percent Hydrocarbons in Samples (Gas Production #10).....	2-30
2-28 Weight Percent Hydrocarbons in Samples (Gas Production #11)	2-31
2-29 Weight Percent Hydrocarbons in Samples (Gas Production #12).....	2-32
2-30 Weight Percent Air Toxics in Light Crude Emissions.....	2-33
2-31 Weight Percent Air Toxics in Heavy Crude Emissions	2-34
2-32 Weight Percent Air Toxics in Gas Production Emissions.....	2-35
3-1 Distribution of Offshore Emitters.....	3-3
3-2 Percent of Total Emission by Range.....	3-3

LIST OF FIGURES (Continued)

<u>Figure</u>		<u>Page</u>
3-3	Comparison of Offshore Sample Bags as Collected and as Analyzed	3-4
3-4	Offshore Production Correlation (CN, OEL)	3-6
3-5	Offshore Production Correlation (VL, Others).....	3-6
3-6	Weight Percent Hydrocarbons in Samples (Offshore #17)	3-9
3-7	Weight Percent Hydrocarbons in Samples (Offshore #18)	3-10
3-8	Weight Percent Hydrocarbons in Samples (Offshore #19)	3-11
3-9	Weight Percent Hydrocarbons in Samples (Offshore #20)	3-12
3-10	Weight Percent Air Toxics in Gulf Offshore Emissions.....	3-13
3-11	MMS Connection and Open-Ended Line Data with API/GRI Offshore Equations.....	3-16
3-12	MMS Valve and Other Data with API/GRI Offshore Equations	3-16
3-13	Distribution of Pacific OCS Emitters	3-17
3-14	Percent of Total Emissions by Range (Pacific OCS Platforms).....	3-17

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EXECUTIVE SUMMARY

INTRODUCTION

The American Petroleum Institute (API) and the Gas Research Institute (GRI) conducted an extensive field study of fugitive hydrocarbon emissions from petroleum production operations. Data were collected from 184,035 components at 20 different sites and used to develop new emission factors and correlation equations. This report contains new emission factors for light crude production sites, heavy crude production sites, gas production sites, and Gulf of Mexico (Gulf) offshore petroleum production operations that supersede those published by API in "Fugitive Hydrocarbon Emissions from Petroleum Production Operations, Volumes I and II," (1980). Emission factors for gas processing plants will be published in a separate report after the collection of additional field data. This report also contains emission correlation equations that can be used to calculate fugitive emissions from individual instrument screening values (ISV) obtained with portable hydrocarbon monitoring instruments at all types of petroleum production facilities.

OBJECTIVES

Objectives of the study were:

1. Development of correlation equations relating instrument screening values to mass emission rates;
2. Development of emission factors;
3. Development of profiles of speciated hydrocarbon emissions including air toxics;
4. Assessment of regional differences in fugitive emissions; and,
5. Assessment of control efficiency of Inspection and Maintenance programs.

STUDY GUIDELINES AND PROCEDURES

The following types of petroleum production facilities were visited:

- Onshore light crude production
- Onshore heavy crude production
- Onshore natural gas production
- Onshore natural gas processing plants
- Gulf of Mexico offshore platforms

At the beginning of each site visit, monitoring personnel met with representatives of the operating company to become oriented with the facility lay-out and safety requirements. Monitoring and sample collection activities started immediately after the orientation meetings. The following precautions were

ES-1

taken to assure that monitoring data and hydrocarbon samples were representative of the normal operating condition of each facility:

- Monitoring work was conducted without petroleum company supervision;
- Components that gave elevated screening values were recorded on confidential field data sheets (these were not shown to oil company personnel until the end of the visit);
- No identification markers were attached to emitting components during the time between screening and hydrocarbon collection;
- Collection of fugitive hydrocarbon emission samples occurred as soon after detection as possible to minimize the possibility of changes due to maintenance activities.

During the first days of each visit, all components were counted, logged, and screened with portable hydrocarbon monitoring instruments equipped with flame ionization detectors. All elevated readings (10 parts-per-million by volume, methane equivalence [ppmv] or more) were recorded; descriptive information about each component that gave an elevated reading was also recorded. [NOTE: Components with ISVs of 10 ppmv or more are referred to in this report as "emitters."]

Approximately 15 percent of the emitters were enclosed in polyethylene tents to collect samples of the fugitive hydrocarbons. [NOTE: This procedure is referred to herein as "bagging".] All of the collected samples were speciated into C1 through C6+ fractions. Approximately 25 percent of the samples were also analyzed for air toxics. Mass emission rates were calculated for all the bagged emitters.

Table ES-1 shows the number of components screened, the number of emitters found, and the number of samples collected at each of the five types of petroleum production facilities. The table also shows the number of samples speciated into C1 through C6+ fractions, and the number analyzed for aromatic air toxics.

Table ES-1. NUMBER OF COMPONENTS SCREENED, EMITTERS FOUND, AND SAMPLES COLLECTED AND ANALYZED FOR THE API/GRI STUDY

FACILITY TYPE	COMPONENTS SCREENED	EMITTERS FOUND*	EMITTERS SAMPLED	ANALYZED C1 -C6+	ANALYZED Air Toxics
Onshore Lt. Crude	48,652	991	165	165	43
Onshore Hvy Crude	13,756	62	30	30	4
Onshore Natural Gas	40,178	1,513	92	92	43
Onshore Gas Plant	35,764	1,615	175	175	40
Offshore Oil/Gas	45,685	615	243	243	38
TOTAL	184,035	4,796	705	705	168

*NOTE: Emitter = ISV $\geq$ 10 ppmv

ES-2

During the inventory task, components were grouped as follows:

1. Connections (CN)
2. Valves (VL)
3. Open Ended Lines (OEL)
4. Compressor Seals (CS)
5. Pump Seals (PS)
6. Pressure Relief Valves (PRV)
7. Dump Lever Arms (DLA)
8. Polished Rod Pumps (ROD)
9. Miscellaneous (MISC)

During data analysis, component types 4 through 9 were combined into a single "Others" category.

Correlation equations were developed from speciation data to show the relationship between ISVs and mass emission rates. A separate correlation equation was sought for each of four component types (CN, VL, OEL, Other) at each of the five types of facility, however, several of the sub-sets of data were found to be statistically identical and were therefore combined by type of facility. "Default zero" emission rates were defined for components with ISVs below 10 ppmv.

Emission factors were developed using the correlation equations and all 184,035 ISVs. This was done by calculating an emission rate for each ISV using the appropriate correlation equation, then adding all calculated emission rates for each facility type/component type combination to give the total expected emission rates. "Average" emission factors (average emissions per installed components) were derived by dividing total emissions by the total number of components. "Leak/No Leak" and "Stratified" emission factors were developed by grouping the data according to ISVs. Speciated weight fractions (C1 through C6+, and air toxics) of fugitive emission were also developed.

RESULTS

Correlation equations were developed for all five types of petroleum production facilities; emission factors were developed for four of the five types of facilities. Additional data are being collected for gas plants after which those emission factors will be calculated and presented in a separate report. Statistical evaluation showed that because many of the correlation equations were statistically equivalent; only eight equations were needed to predict emissions from the five types of facilities.

Emission factors were developed for the same categories as the correlation equations (except gas processing plants). Speciation factors were developed for each site type. The five types of facilities were defined as follows:

- Onshore light crude production sites. This group included onshore production sites that produced only oil and sites that produced oil mixed with gas. Oil produced at these sites had an API gravity of 20 or more.
- Onshore heavy crude production sites. Sites that produced oil with an API gravity less than 20 were designated as heavy crude sites. Thermally enhanced oil recovery sites were included in this category.
- Onshore gas production sites. This category included sites that produced dry natural gas, natural gas liquids, condensate, or a very minor amount of light oil along with the produced gas. Equipment located along-side the wells or at gathering stations were included in this category. Co-located gas plants were counted in the Onshore gas processing plant category.
- Onshore gas processing plants. Onshore plants that process natural gas and/or natural gas liquids were included in this category. Wells located adjacent to the gas plant were counted in the Onshore gas production category instead of this category.
- Offshore oil and gas production platforms. All offshore operations were included in this category.

No evidence of statistical differences among different regions of the country was found except for offshore platforms. Comparison of the data produced by this study of Gulf platforms with study data published by the US Minerals Management Service (MMS) in "Fugitive Hydrocarbon Emissions From Pacific OCS Facilities, Volumes 1 and 2," (November 1992), indicated that Pacific platforms have a lower leak frequency than Gulf platforms. Offshore platforms in either area have lower leak frequencies than onshore facilities.

Ninety percent of fugitive hydrocarbon emissions observed in this study came from components that had large leaks (usually less than one percent of the total installed components). This suggests that an inspection and maintenance program that can reduce the number of large leaks may be effective in reducing total fugitive hydrocarbon emissions.

Correlation Equations

Correlations between ISVs and mass emission rates were calculated from laboratory analyses for ISVs above 10 ppmv. Correlation equations were developed by regressing the natural logarithm of total hydrocarbon emissions (ln THC) on the natural logarithm of the instrument screening values (ln ISV). A simple linear regression (least squares fit) was then calculated and converted from log space to arithmetic space using a scale bias correction factor. Table ES-2 gives the correlation equations for all types of sites.

ES-4

Table ES-2. CORRELATION EQUATIONS

FACILITY	COMPONENT TYPE	CORRELATION EQUATION
Onshore Light Crude	CN, VL, OEL	$\text{THC}(\text{lb/day}) = 8.61 \times 10^{-5}(\text{ISV ppmv})^{0.83}$
Onshore Light Crude	Other	$\text{THC}(\text{lb/day}) = 1.24 \times 10^{-3}(\text{ISV ppmv})^{0.61}$
Onshore Heavy Crude	All	$\text{THC}(\text{lb/day}) = 3.29 \times 10^{-5}(\text{ISV ppmv})^{0.89}$
Onshore Gas Production	CN, OEL	$\text{THC}(\text{lb/day}) = 8.04 \times 10^{-6}(\text{ISV ppmv})^{1.02}$
Onshore Gas Production	VL, Other	$\text{THC}(\text{lb/day}) = 9.79 \times 10^{-5}(\text{ISV ppmv})^{0.96}$
Onshore Gas Plant	All	$\text{THC}(\text{lb/day}) = 1.79 \times 10^{-4}(\text{ISV ppmv})^{0.87}$
Offshore Oil & Gas	CN, OEL	$\text{THC}(\text{lb/day}) = 1.04 \times 10^{-5}(\text{ISV ppmv})^{0.99}$
Offshore Oil & Gas	VL, Other	$\text{THC}(\text{lb/day}) = 3.30 \times 10^{-4}(\text{ISV ppmv})^{0.87}$

NOTE: All correlation equations and emission factors presented in this report are based on ISVs obtained within 1 cm of the component surfaces.

Default Zero Emission Factors

The correlation equations predict emission rates from 0.00008 to 0.00505 lb/day for components with ISVs of 10 ppmv depending on the facility type and component type. In this report, all components with screening values below 10 ppmv have been assumed to leak at rates that produce ISVs of 5 ppmv. Table ES-3 gives the THC default zeros.

Table ES-3. DEFAULT ZERO THC EMISSION FACTORS

FACILITY TYPE	COMPONENT TYPE	DEFAULT ZERO
Onshore Light Crude	CN, VL, OEL	0.00033 lb/day-component
Onshore Light Crude	Other	0.00331 lb/day-component
Onshore Heavy Crude	All	0.00014 lb/day-component
Onshore Gas Production	CN, OEL	0.00004 lb/day-component
Onshore Gas Production	VL, Other	0.00046 lb/day-component
Onshore Gas Plant	All	0.00073 lb/day-component
Offshore Oil & Gas	CN, OEL	0.00005 lb/day-component
Offshore Oil & Gas	VL, Other	0.00134 lb/day-component

Average Emission Factors

Average emission factors are used to predict fugitive hydrocarbon emissions when the only information available about a site is the number of components installed. Average factors for four types of sites (excluding gas plants) were developed by dividing total emissions by the total number of installed components. Average emission factors for individual component types were developed by dividing the component type's contribution to total emissions by the number of those components. Table ES-4 gives the overall average THC emission factors for each facility type; Table ES-5 gives component specific average THC emission factors for each facility type/component type combination.

Table ES-4. AVERAGE THC EMISSION FACTORS
(Overall)

Onshore Light Crude	All	0.0085 lb/day-component
Onshore Heavy Crude	All	0.0002 lb/day-component
Onshore Gas Production	All	0.0233 lb/day-component
Offshore Oil & Gas	All	0.0055 lb/day-component

Table ES-5
AVERAGE THC EMISSION FACTORS
(Component specific)
[lb/day-component]

	CONNECTIONS	VALVES	OPEN-ENDED	OTHERS
Onshore Light Crude	0.0041	0.0197	0.0351	0.0991
Onshore Heavy Crude	0.0001	0.0002	0.0010	0.0007
Onshore Gas Production	0.0038	0.1063	0.0107	0.2870
Offshore Oil & Gas	0.0006	0.0217	0.0099	0.1036

Leak/No Leak Emission Factors

Another method of calculating fugitive hydrocarbon emissions is to screen components and determine the number above and below a leak definition (in ppmv). "Leak/No Leak" THC emission factors are given in Table ES-6.

Table ES-6. "LEAK/NO-LEAK" THC EMISSION FACTORS
(Pounds/Day-Component)

FACILITY TYPE	COMP. TYPE	No Leak <10,000 ppmv	Leak ≥10,000 ppmv
Onshore Light Crude	CN, VL, OEL	0.00060	0.91
Onshore Light Crude	Other	0.01660	0.878
Onshore Heavy Crude	All	0.00016	0.119
Onshore Gas Production	CN, OEL	0.00021	0.380
Onshore Gas Production	VL, Other	0.00546	2.45
Gulf Offshore Oil & Gas	CN, OEL	0.00012	0.183
Gulf Offshore Oil & Gas	VL, Other	0.00267	2.22

Stratified Emission Factors

Stratified THC emission factors given in Table ES-7 show the emission rates for components with ISVs below 10 ppmv; from 10 to 9,999 ppmv; from 10,000 to 99,999; and equal to or greater than 100,000 ppmv.

ES-6

Table ES-7. "STRATIFIED" THC EMISSION FACTORS
(Pounds/Day-Component)

FACILITY TYPE	COMPONENT TYPE	INSTRUMENT SCREENING RANGE			
		<10 ppmv	10 to 9,999	10,000 to 99,999	≥ 100,000 ppmv
Onshore Light Crude	CN, VL, OEL	0.00033	0.0274	0.395	1.22
Onshore Light Crude	Other	0.00331	0.0610	0.365	1.39
Onshore Heavy Crude	All	0.00014	0.0046	0.119	na
Onshore Gas Production	CN, OEL	0.00004	0.0112	0.126	1.01
Onshore Gas Production	VL, Other	0.00046	0.0871	0.756	6.18
Offshore Oil & Gas	CN, OEL	0.00005	0.0099	0.097	0.927
Offshore Oil & Gas	VL, Other	0.00134	0.1187	1.071	7.39

Speciated Hydrocarbon Factors

Tables ES-2 through ES-7 present correlation equations and emission factors for calculating THC (all hydrocarbon species combined). Emission rates for individual hydrocarbon species can be calculated by multiplying THC emissions by the weight fractions given in Table ES-8.

Table ES-8
SPECIATED FUGITIVE EMISSION FACTORS
(Weight Fraction of THC emissions in each category)

	METHANE	NMHC	VOC	C6+	BENZENE	TOLUENE	ETHYL- BENZENE	XYLENES
Onshore Light Crude	0.613	0.387	0.292	0.02430	0.00027	0.00075	0.00017	0.00036
Onshore Heavy Crude	0.942	0.058	0.030	0.00752	0.00935	0.00344	0.00051	0.00372
Onshore Gas Production	0.920	0.080	0.035	0.00338	0.00023	0.00039	0.00002	0.00010
Offshore Oil & Gas	0.791	0.210	0.110	0.00673	0.00133	0.00089	0.00016	0.00027

NOTES:

1. Emission factor = Speciated Emissions/Total Emissions
2. NMHC = Non-methane hydrocarbon
3. VOC = Propane and heavier hydrocarbon
4. Many hydrocarbons are included in more than one group, for example, C6+ is also included in the NMHC and VOC groups.

SUMMARY/CONCLUSIONS

Accuracy of Screening and Bagging Techniques

Instrument screening values are influenced by such things as wind speed and direction, instrument dynamics (calibration, battery charge, flow rate), and sampling protocols. As a result, there is a wide

variation in ISVs found for each mass emission rate. Statistical analysis of the relationship between ISVs and mass emission rates yields a "regression correlation coefficient" (r) which indicates how closely the two variables are related. A coefficient of 1.00 indicates perfect correlation. Regression correlation coefficients for the various equations developed from API/GRI data ranged from 0.56 to 0.86; a single equation developed by combining all the data into one set had a correlation coefficient of 0.71. This compares favorably with the four equations published by the EPA in "Protocols for Equipment Leak Emission Estimates" (June 1993) that ranged from 0.45 to 0.87, and with the regression correlation coefficient published with the MMS Pacific OCS platform data which is 0.79.

Speciated Emissions and Air Toxics

Methane was the major fugitive hydrocarbon at all types of petroleum production sites. Hexane was found in levels of 2 percent by weight or less, while benzene and toluene were found at levels below 1 weight percent. Concentrations of xylenes and ethyl-benzene were usually near the laboratory method detection limits.

Regional Differences in Emissions

No apparent regional differences have been found except for offshore platforms.

Inspection and Maintenance

More than 90 percent of the total emissions came from components with ISVs of 10,000 ppmv or more. Inspection and Maintenance (I&M) practices that are effective in reducing the number of ISVs at 10,000 ppmv or more could significantly reduce fugitive hydrocarbon emissions.

SECTION 1 STUDY METHODOLOGY

INTRODUCTION

In 1980, the American Petroleum Institute (API) published "Fugitive Hydrocarbon Emissions from Petroleum Production Operations, Volumes I and II" that contained fugitive hydrocarbon emission factors for onshore and offshore petroleum production operations. Separate emission factors were given for various types of connections, valves, open-ended lines (drains and sample connections), pressure relief valves, pump and compressor seals, hatches, diaphragms, meters, sight glasses, and pits at each of three strata of facilities: 1) Onshore producing operations, 2) Offshore producing operations, and 3) Gas plant operations. Approximately 150 different emission factors were given for each stratum. Speciation information for the factors was presented as average weight percents of C1, C2, C3, C4, C5, and C6+ hydrocarbon for each stream type. The report did not contain information on air toxics emissions. The effectiveness of inspection and maintenance programs was investigated, but results were inconclusive.

Changes in petroleum production facility equipment and operations since the factors were published, as well as changes in the regulatory environment, have resulted in significant reductions of fugitive hydrocarbons emissions. As a result, the 1980 API factors overpredict emissions from modern facilities.

Objectives

Beginning in 1990, API and the Gas Research Institute (GRI) conducted a study to:

1. Develop correlation equations relating instrument screening values (ISVs) to mass emission rates;
2. Develop new fugitive hydrocarbon emission factors;
3. Develop profiles of speciated hydrocarbon emissions including air toxics;
4. Assess regional differences in fugitive emissions;
5. Assess control efficiency of Inspection and Maintenance programs.

Scope

This report presents data collected at four light crude production sites, four heavy crude production sites, four gas production sites, four gas processing plants, and four Gulf of Mexico platforms. Correlation equations were developed from data collected at all five types of facilities. Fugitive hydrocarbon emission factors and air toxics weight fractions were developed from data at four types of

sites. A separate report on fugitive hydrocarbon emission factors and air toxics weight fractions for gas plants will be published after more field data are collected in a joint research effort with the EPA.

The 1980 emission factors for connections, valves, and open-ended lines are directly superseded by the new emission factors developed in this study. The limited number of uncontrolled pressure relief valves, pump seals, compressor seals, and other components found during the study did not provide enough data to allow development of new factors for these components as separate types. Instead these and other miscellaneous components were grouped into one category called "Others". The study produced two types of emission factors: 1) emission factors for use with component counts and, 2) emission factors for use with ISVs. Separate correlation equations were developed for connections, valves, open-ended lines, and other components. Emissions were speciated according to hydrocarbon length (number of carbon atoms) and type (aromatic and nonaromatic hydrocarbons).

DESCRIPTION OF METHODOLOGY

Sixteen onshore sites and four offshore sites were visited in the contiguous United States. A total of 184,035 components was screened according to US EPA Method 21 guidelines using portable monitoring instruments. A total of 4,796 components gave ISVs of 10 parts-per-million by volume methane equivalence (ppmv) or more. These components are referred to in this report as "emitters". Mass emission rates from approximately 15 percent of the emitters were quantified by enclosing the components in polyethylene tents or bags ("bagging") and collecting samples of the escaping hydrocarbons in Tedlar sample bags. Mass emission rates from the bagged emitters were used to develop correlation equations; correlation equations were used to develop emission factors. The five types of petroleum production facilities visited were:

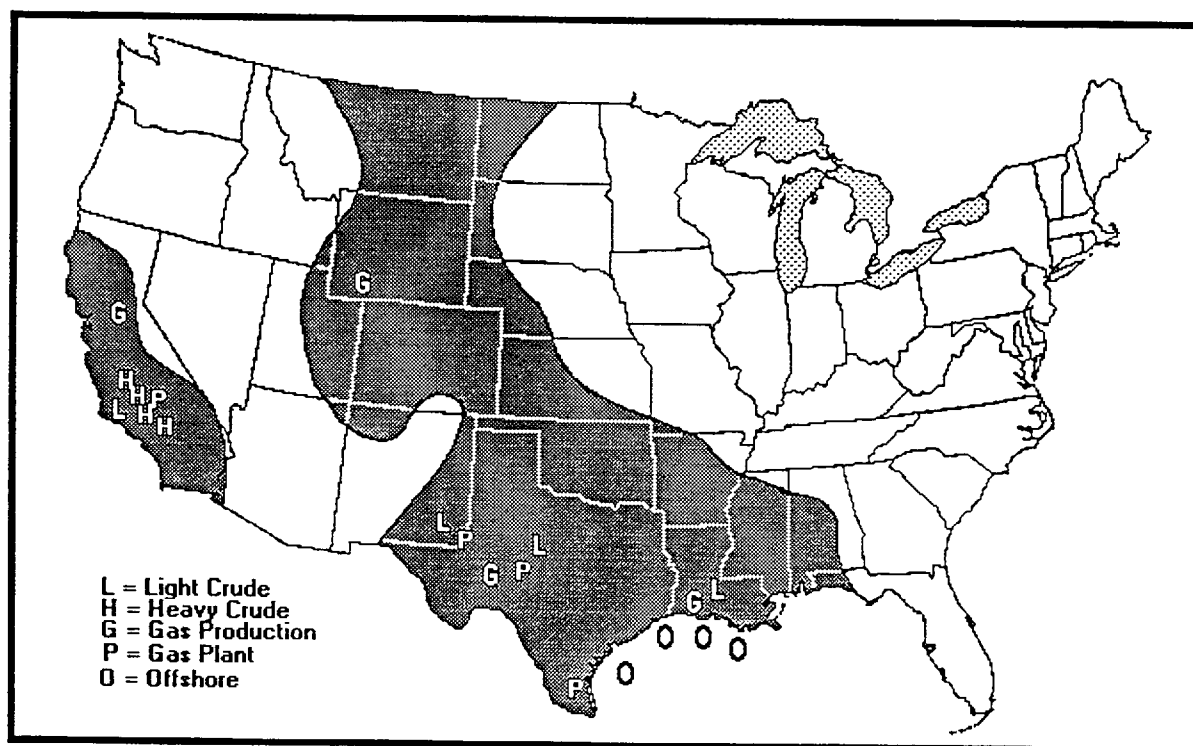
- Onshore light crude production sites. This group included onshore production sites that produced only oil and sites that produced oil mixed with gas. Oil produced at these sites had an API gravity of 20 or more.
- Onshore heavy crude production sites. Sites that produced oil with an API gravity less than 20 were designated as heavy crude sites. Thermally enhanced oil recovery sites were included in this category.
- Onshore gas production sites. This category included sites that produced dry natural gas, natural gas liquids, condensate, or a very minor amount of light oil along with the produced gas. Equipment located beside the wells or at gathering stations were included in this category. Co-located gas plants were counted in the Onshore gas processing plant category.
- Onshore gas processing plants. Onshore plants that process natural gas and/or natural gas liquids were included in this category. Wells located next to the gas plant were counted in the Onshore gas production category instead of this category.

- Offshore oil and gas production platforms. All offshore operations were included in this category.

Study Sites Selection

Figure 1-1 shows the approximate location of the sites visited. The figure also shows the two major regions of petroleum production in the contiguous United States. These regions account for more than 90 percent of total oil and gas production in the lower 48 states. Four of the onshore sites were light crude production fields, four were heavy crude production fields, four were dry gas production fields, and four were gas plants.

Figure 1-1. 1993 API/GRI STUDY SITES



NOTE: Darkened areas are regions of major oil and gas production.

Table 1-1 lists the number of components screened at each site, the number of emitters found, and the number of samples collected. Site numbers are assigned by facility type and number of components screened.

Table 1-1. SITES INCLUDED IN THE 1993 API/GRI STUDY

FACILITY TYPE	SITE NO.	COMPONENTS SCREENED	EMITTERS FOUND	SAMPLES COLLECTED
Light Crude	1	27,155	522	43
Light Crude	2	14,620	290	39
Light Crude	3	4,095	84	58
Light Crude	4	2,782	95	28
Heavy Crude	5	6,362	19	9
Heavy Crude	6	2,799	21	9
Heavy Crude	7	2,696	8	6
Heavy Crude	8	1,899	14	8
Gas Production	9	14,066	324	23
Gas Production	10	9,374	316	36
Gas Production	11	9,094	628	22
Gas Production	12	7,644	245	36
Gas Plant	13	11,235	416	61
Gas Plant	14	10,673	616	30
Gas Plant	15	7,786	303	42
Gas Plant	16	6,070	280	34
Offshore Platform	17	15,734	218	76
Offshore Platform	18	10,967	145	56
Offshore Platform	19	10,271	93	61
Offshore Platform	20	8,713	159	59
TOTALS		184,035	4,796	736

Screening Procedures

Components were screened using commercially available portable monitoring instruments that met the following requirements of EPA Method 21 -- "Determination of Volatile Organic Compounds Leaks":

1. The instruments had flame ionization detectors (FID);
2. The instruments responded to hydrocarbons in concentrations between 1 and 10,000 ppmv in air and the instrument scale was readable within 2.5 percent; dilution techniques were employed when needed to extend the instrument range above 10,000 ppmv.
3. The probe tips did not exceed 0.25 inches in outside diameter;
4. The instruments contained electrically driven pumps that sampled between 0.1 and 3.0 liters per minute;
5. The instruments were intrinsically safe;
6. The instruments responded to hydrocarbons within 5 seconds.

At the beginning of each day, all instruments were calibrated near zero, at mid-range, and near their upper measurement limits with zero air and certified mixtures of methane-in-air. Calibrations were checked throughout the day.

The instruments had response factors between 0.5 and 1.5 for methane, ethane, propane, butane, pentane, hexane, benzene, toluene, ethyl-benzene, and xylenes, which were the major hydrocarbons found in petroleum production fugitive emissions. [NOTE: Field measurements were not corrected for variability of instrument response to different hydrocarbons (response factors)].

Each site was subdivided into small geographic sub-areas containing from 50 to 200 equipment components. All valves, connections, pump seals, compressor seals, pressure relief devices, open-ended lines, meters, sight glasses, hatches, and vents in each sub-area were inventoried and screened. "Protocols for Equipment Leak Emission Estimates" (June 1993) recommends the following, "hold the probe tip just over (a dirty) surface to avoid scooping up contaminants". The API/GRI study was conducted with the inlet probe of the monitoring instrument held within 1 cm of all points of possible emissions to prevent contamination and assure consistent screening values throughout the study. This was consistent with petroleum industry practice.

The EPA protocol says that two additional methods of protecting against contamination are using flexible plastic tubing as an expendable extension to the probe tip and packing the tubing with untreated fiberglass. Plastic tubing without fiberglass packing was sometimes used during the API/GRI study. The instruments had internal dust filters which were cleaned on a regular basis.

Each component was screened by moving the instrument probe along all areas of possible leakage while observing the instrument readout. When an increased reading was observed, the probe was moved slowly across the area until the maximum meter reading was obtained. The probe inlet was held at the point of highest reading for at least 10 seconds (twice the instrument response time). The maximum reading was recorded as the ISV.

The stems of valves were screened at the opening between the stems and packing nuts, and all other points of possible emissions. Body seals and plugs were also screened. Emissions from any of these areas were recorded as "Valve emissions". The connections between valve bodies and process piping were counted as "Connections". The ends of valves open to atmosphere, or connected to short pieces of pipe which in turn were open to atmosphere were counted as "Open-Ended Lines".

Flanges, threaded connections, and tubing fittings were screened at all possible points of emissions. Emissions from these components were recorded as "Connection" emissions.

Many pump seals and compressor seals had been enclosed and routed to flare headers or vapor recovery systems. These components were not counted or screened. Accessible pump and compressor seals were screened with traverses at the outer circumference surfaces of the shafts and seal interfaces. Emissions from these areas were recorded as "Compressor Seal" or "Pump Seal" emissions. Plugs, flanges, threaded connections, and valves on pumps and compressors were also screened. Emissions from these components were recorded as emissions from connections, valves, or open-ended lines, not as compressor or pump emissions.

Pressure relief valves (PRV) connected to flare headers were not counted or screened. PRVs that vented to atmosphere were screened by holding the sampling probe at the center of the exhaust areas.

Other sources such as process drains, degassing vents, access doors and hatches, were screened at all openings and other points of possible emission. If the openings were less than one inch diameter, a single reading was taken. Larger openings were screened around the entire perimeter.

The types and numbers of components screened in each sub-area were recorded on field data sheets. All ISVs of 10 ppmv or more were recorded on the field data sheets along with descriptions of the sizes and types of components giving elevated readings.

Bagging Procedures

EPA Protocol guidelines for the "Vacuum Method" were followed with some additional procedures to improve collection. Each component was re-screened immediately before bagging to locate the point of highest emissions. A sampling tube was then attached to the component with the tube inlet placed within 1 cm of the point of highest emissions. The other end of the tube was attached to a rotameter which in turn was connected to an electrically driven sampling pump capable of drawing between 1.5 and 20 liter per minute. A second tube (ambient air supply tube) was attached to the opposite side of the component. The component and tubes were then enclosed in a tight-fitting 4 mil thick polyethylene bag, the edges of the bag being heat-sealed and/or taped to prevent uncontrolled entry of air into the bag.

When the pump was started, the bag collapsed, thus preventing loss of hydrocarbon. The reduced pressure inside of the bag caused ambient air to be drawn in through the ambient air supply tube. The flow rate of ambient air into the bag was monitored with a second rotameter attached to the inlet side of the ambient air supply tube. If the flow through the two rotameters (bag inlet and bag outlet) was not

comparable, the bag was resealed. [NOTE: Concentrations of hydrocarbon in the ambient air were usually less than 5 ppmv. At a typical sampling rate of 3 liters per minute, the additional hydrocarbon drawn into the bag with the ambient air was less than 0.00000003 lb/minute (0.00004 lb/day) which had a negligible effect on the development of correlation equations and subsequent development of emission factors.]

When a controlled flow rate through the bag was achieved, the pump outlet was measured with the hydrocarbon monitoring instrument until a constant reading was recorded for three consecutive 30-second periods. A Tedlar sample bag was then attached to the pump outlet and filled and emptied three times. The Tedlar sample bag was then filled for the fourth time and sent to an off-site laboratory for analysis.

After the Tedlar sample bag had been filled for the final time, the pump outlet was again measured with the portable hydrocarbon monitoring instrument until a constant reading is recorded for three consecutive 30-second periods. The polyethylene bag is then completely removed from the component and the component is re-screened with the portable monitoring instrument to give a "post-bagging" reading.

The pre-bagging and post-bagging screening values are recorded on the field data sheets with their times of measurement. Instrument readings of the pump outlet before and after sample collection are also recorded with their exact times of measurement. The field data sheets also contain sample identification numbers, component types and locations, pump identification numbers, pump flow rates, dates, and names of field personnel conducting sample collections.

Chain of custody forms are prepared which included sample identification numbers, dates and times of sample collection, readings of the pump outlet (in ppmv) just before filling the bags, and signatures of field technicians transporting the samples. The forms are signed and dated by the receiving laboratories, and the laboratory identification numbers are recorded beside the field identification numbers.

The program design includes a feed-back mechanism to adjust the number and types of components selected for mass emissions quantification. Information obtained at the first sites showed that approximately 80 percent of the components are connections, 17 percent are valves, 2 percent are open-ended lines and the remaining 1 percent is composed of uncontrolled compressor seals, uncontrolled pump seals, polished rod stuffing boxes, dump lever arm seals, hatches, vents,

uncontrolled pressure relief devices, and other components. The information also showed that more than 90 percent of the fugitive emissions comes from connections, valves and open-ended lines with ISVs of 10,000 ppmv or more. As a result, bagging at later study sites was directed mainly at large emitters in these three types of components.

Laboratory Procedures

Gas chromatography (GC) is used to separate the hydrocarbons by species. Aromatic hydrocarbons are quantified using photo-ionization detectors or by mass spectroscopy (MS); nonaromatic hydrocarbons are quantified using flame ionization detectors. Concentrations of the following hydrocarbon species are reported in ppmv to three significant digits:

- Methane (C1)
- Hydrocarbons containing two carbon atoms per molecule (C2)
- Hydrocarbons containing three carbon atoms per molecule (C3)
- Hydrocarbons containing four carbon atoms per molecule (C4)
- Hydrocarbons containing five carbon atoms per molecule (C5)
- Hydrocarbons containing six or more carbon atoms (C6+)
- Benzene
- Toluene
- Ethyl-benzene
- meta and para Xylenes
- ortho Xylene

Speciated laboratory analyses in parts per million by volume are converted to mass emission rates using the following molecular weight assumptions:

CHEMICAL SPECIES	ASSUMED MOLECULAR WEIGHT
C1	16
C2	30
C3	44
C4	58
C5	72
C6+	86
Benzene	78
Toluene	92
Ethyl-benzene	106
Xylenes	106

Quality Assurance/Quality Control Procedures

Approximately 15 percent of the analyses were replicated in the laboratory to assess precision. Field blanks and bags filled with calibration gases of known concentrations were given coded identification numbers and sent to the laboratory to assess accuracy. Duplicate samples of fugitive emissions were collected from several of the components. Some of the duplicate samples were given coded

identification numbers and sent to the same laboratory to assess precision of the analyses; others were sent to a second laboratory for comparison analysis.

API conducted an independent audit of the field contractor and laboratories used in the program to examine site sample collection forms, chain of custody forms and sample identity designations, laboratory data (GC, GC/MS tracings), calibration records and reported values. In general, the API auditor found the data to be well organized and trackable. The few discrepancies found in the data were discussed and resolved.

DATA MANAGEMENT

Actual ISVs of 10 ppmv or more were recorded for 4,796 components. Seven-hundred and thirty-six (736) samples of fugitive hydrocarbon were collected and analyzed. Correlation equations were developed from the bagging data and ISVs; emission factors were developed from the correlation equations, ISVs, and component inventories. Appendix A contains detailed descriptions of methods used to develop correlation equations and emission factors.

Development of Correlation Equations

Because fugitive emission concentrations tend to be log-normally distributed, model equations have been derived over the past several years by regressing the natural logarithm of total hydrocarbon emissions, (ln(THC)), on the natural logarithm of the ISV, (ln(ISV)). The model equations have been typically of the form:

$$\ln(\text{THC}) = \alpha + \beta \ln(\text{ISV}) \quad [\text{Equation for log space}] \quad \text{Eq. 1-1}$$

or

$$\text{THC} = e^{\alpha} (\text{ISV})^{\beta} \quad [\text{Equation for arithmetic space}] \quad \text{Eq. 1-2}$$

where α and β denote respectively the intercept and slope of the regression model on the log-log scale. This model equation form was used to develop correlation equations for the API/GRI data.

A general Analysis of Variance model was used to allow different intercepts and slopes for each facility type/component type combination. Through a series of iterations, terms that were not statistically significant were excluded from the model until only significant terms remained.

Linear regressions calculated in log space are biased low because of the relationship between actual numbers and their logarithms. When making the transformation of equations from log space to arithmetic space, intercepts have to be adjusted to produce unbiased predictions. Adjustments were made using the following scale bias correction factor (SBCF):

$$\text{SBCF} = 1 + \frac{(m-1)^1 \cdot T}{m^1 \cdot 1!} + \frac{(m-1)^3 \cdot T^2}{m^2 \cdot 2! \cdot (m+1)} + \frac{(m-1)^5 \cdot T^3}{m^3 \cdot 3! \cdot (m+1) \cdot (m+3)} + \dots \quad \text{Eq. 1-3}$$

Where:

$T = 0.5 \cdot (\text{mean square error of the regression})$

$m = \text{number of data pairs}$

Correlation equations developed from the new data are given in Sections 2 and 3 of this report.

Development of Emission Factors

Five ISV ranges were defined to account for the distribution of the number of components and their emission contributions:

$\geq 100,000$ ppmv
 10,000 to 99,999 ppmv
 1,000 to 9,999 ppmv
 10 to 999 ppmv
 <10 ppmv

Bagged hydrocarbon emissions were then modeled to verify that average emissions in each range were homogeneous across the facility type/component type categories chosen during correlation equation development. The screening value of each component was entered into the appropriate correlation equation and estimated emissions were obtained.

The lower useful limit of the hydrocarbon monitoring instrument is considered to be 10 ppmv. Ambient levels of methane in the atmosphere are approximately 2 ppmv or more. Further, difficulties with equipment calibration, battery fade-out, and other operator induced variables make readings of less than 10 ppmv highly unrepeatable. For these reasons, ISVs of less than 10 ppmv were entered into the equations as 5 ppmv. The total of the estimated THC emissions was then calculated for each of the five ranges. Finally, the average emissions were computed as total emissions divided by total number of components. Average emission factors for specific component types were developed by dividing the component type's contribution to total emissions by the number of those components.

"Leak/No-Leak" emission factors were calculated for each site. Stratified emission factors were developed for four ranges: ISVs below 10 ppmv; from 10 to 9,999 ppmv; from 10,000 to 99,999; and equal to or greater than 100,000 ppmv.

SECTION 2

ONSHORE RESULTS AND ANALYSIS

DATA COLLECTION

A total of 138,350 components at 16 onshore sites was inventoried and screened using portable hydrocarbon analyzers. The sites were divided into sub-areas. Inventories were prepared by counting the connections (CN), valves (VL), open-ended lines (OEL), compressor seals (CS), pump seals (PS), pressure relief valves (PRV) and miscellaneous components (Misc) contained in each sub-area. All components in each sub-area were screened according to EPA Method 21 guidelines. Two sites contained thousands of wells; at these sites it was necessary to select a limited number of the sub-areas for screening.

Full descriptions of 4,181 onshore components found to have instrument screening values (ISV) of 10 parts per million by volume (ppmv) methane equivalence or more were recorded on field data sheets. These components are referred to as "emitters" in this report. Samples of fugitive hydrocarbons from 473 emitters were collected and speciated for nonaromatic hydrocarbons. A total of 144 samples that had high total hydrocarbon content was also analyzed to determine benzene, toluene, xylenes, and ethyl-benzene concentrations.

Appendix B of this report contains inventory and screening data for all sites. Appendix C lists the location, component type, and ISV for each emitter. Appendix D contains nonaromatic speciation data. Appendix E contains aromatic speciation data.

Table 2-1 contains a summary of the number and types of components screened at each onshore site and the number of emitters found. In the table, ISVs are grouped into one of six ranges: 10 to 99; 100 to 499; 500 to 999; 1,000 to 9,999; 10,000 to 99,999 and $\geq 100,000$ ppmv.

Table 2-1. COMPONENTS SCREENED AND EMITTERS FOUND AT ONSHORE SITES

SITE	COMPONENTS SCREENED								EMITTERS BY SCREENING RANGE (ppmv)						
	CN	VL	OEL	CS	PS	PRV	Misc	ALL	10 to 99	100 to 499	500 to 999	1,000 to 9,999	10,000 to 99,999	100 k plus	ALL
1	20767	6121	143	6	11	0	107	27155	84	78	30	83	76	171	522
2	12041	2010	378	1	6	14	170	14620	39	59	28	56	49	59	290
3	3040	867	87	4	4	18	75	4095	13	12	8	24	18	9	84
4	2155	520	85	2	2	4	14	2782	25	18	2	15	20	15	95
5	5282	890	127	0	0	2	61	6362	11	5	1	2	0	0	19
6	2208	446	106	0	0	0	39	2799	13	4	0	2	2	0	21
7	2127	407	110	0	0	8	44	2696	5	0	1	2	0	0	8
8	1433	330	96	0	0	3	37	1899	12	2	0	0	0	0	14
9	11990	1815	215	8	8	6	24	14066	29	58	21	90	82	44	324
10	7171	1758	344	1	0	45	55	9374	49	71	26	54	86	30	316
11	7324	1238	269	25	2	208	28	9094	22	61	9	218	231	87	628
12	6027	1248	223	15	0	112	19	7644	49	36	14	58	55	33	245
13	8463	2427	278	14	21	32	0	11235	29	89	25	107	56	110	416
14	8110	2141	229	29	44	74	46	10673	54	81	28	167	207	79	616
15	6310	1296	71	20	26	28	35	7786	12	34	17	80	97	63	303
16	4781	1127	86	26	15	31	4	6070	9	36	12	57	115	51	280
	109229	24641	2847	151	139	585	758	138350	455	644	222	1015	1094	751	4181

NOTE: CN = Connection; VL = Valve; OEL = Open-Ended Line; CS = Compressor Seal; PS = Pump Seal; PRV = Pressure Relief Valves; Misc = Miscellaneous.

Approximately 10 percent of the emitters in each range were bagged to collect fugitive hydrocarbons for analysis. Extra samples were collected from three categories: 500 to 999 ppmv; 1,000 to 9,999 ppmv; and $\geq 100,000$ ppmv. The number of emitters found and samples collected are shown in Table 2-2.

Table 2-2. ONSHORE EMITTERS BY SCREENING RANGE (ppmv)

	Below 10	10 to 99	100 to 499	500 to 999	1,000 to 9,999	10,000 to 99,999	100,000 plus
Emitters	NA	455	644	222	1015	1094	751
Samples	25	47	65	32	119	71	113

NA: This study classified components with ISV below 10 ppmv as non-emitters.

The distribution of all emitters found at onshore sites, arranged by emission rate, is shown in Figure 2-1. The contribution of each group of emitters to total emissions (as determined from laboratory analyses) is shown in Figure 2-2. About 85 percent of total mass emissions came from individual emissions of 1 lb/day or more (0.18 tons/yr); twelve percent came from individual emissions between 0.125 and 0.999 lb/day (0.02 to 0.18 tons/yr); while about three percent came from emitters with rates of 0.1249 lb/day or less (0.02 tons/yr or less).

Figure 2-1. DISTRIBUTION OF ONSHORE EMITTERS
[Based on Laboratory Analyses]
(From 138,350 Components Screened)

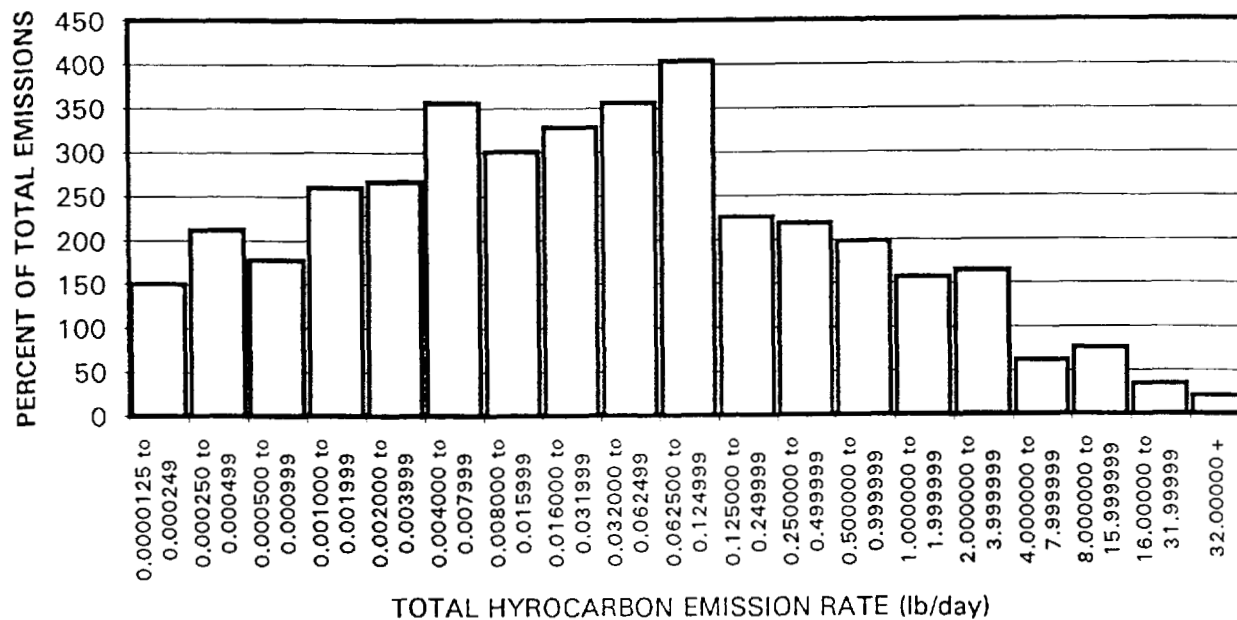
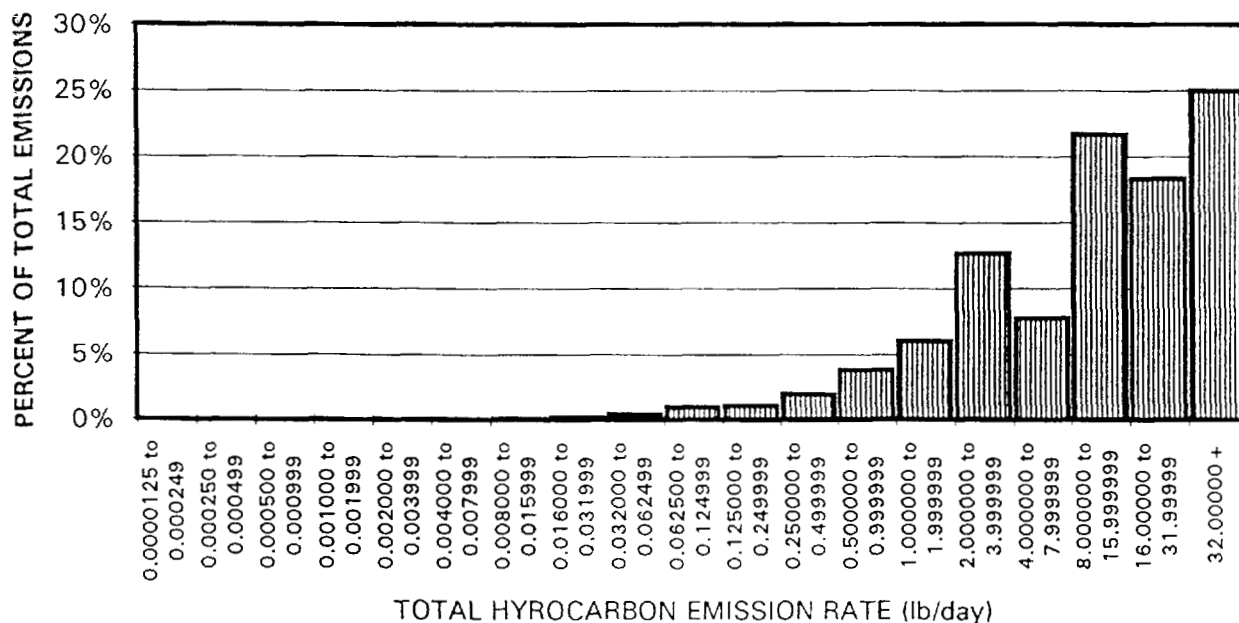


Figure 2-2. PERCENT OF TOTAL EMISSIONS BY RANGE
[Based on Laboratory Analyses]



The contributions of five ISV emitter ranges to total emissions are shown in Table 2-3. Approximately 93 percent of all emissions came from leaks that equal or exceed 10,000 ppmv. The remaining 7 percent came mostly from the 1,000 to 9,999 ppmv ISV range; only 0.7 percent came from emitters with ISV from 10 to 999 ppmv and 1.8 percent came from ISV <10 ppmv. The data in Table 2-3 suggests that all emitters with ISVs from 10 to 9,999 ppmv can be combined into a single group without compromising the ability to predict emissions.

Table 2-3. CONTRIBUTION OF EACH SCREENING RANGE TO TOTAL EMISSIONS

	<10 ppmv	10 to 999 ppmv	1,000 to 9,999	10,000 to 99,999	100,000 plus
Components in Range	134,169	1,321	1,015	1,094	751
Average Rate (lbs/day- component)	0.00043	0.0174	0.146	0.601	3.21
Total Emissions (lbs/day)	58	23	148	657	2,414
Percent of Total	1.8%	0.7%	4.5%	19.9%	73.1%

QUALITY ASSURANCE/QUALITY CONTROL

Samples were speciated into six nonaromatic groups (C1, C2, C3, C4, C5, and C6+); some were also speciated into four aromatic types (benzene, toluene, ethyl-benzene, and xylenes). Approximately 15 percent of the samples were analyzed twice to evaluate laboratory precision. Table 2-4 shows the variation in results from the first and second analyses for nonaromatic hydrocarbons. (NOTE: The methane concentration was often so much higher than the concentration of other hydrocarbons that two separate runs were needed for each analysis: a diluted run to quantify methane and a more concentrated run to quantify the remaining nonaromatic hydrocarbons. Usually only the "methane run" or "nonmethane run" was repeated as a quality assurance check; therefore many of the analyses shown in Table 2-4 have "na" indicating the species that were not analyzed twice.)

Figure 2-3 graphically shows methane concentrations from Table 2-4. Samples that had the same or nearly the same concentration in both analyses fall on the diagonal line across the figure. Data points below the diagonal indicate second analyses with lower methane content than the corresponding first analyses; data points above the diagonal indicate second analyses with higher methane content than the corresponding first analyses. The figure shows that first and second analyses for methane had good agreement for the entire range from 3 to nearly 1,000,000 ppmv in the sample bag. The correlation equation of the least squares linear regression of natural

log(second Methane concentration) versus natural log(first Methane concentration) is 0.99983 indicating a very high correlation. Figures 2-4 through 2-8 graphically show the correlation of repeated analyses for other nonaromatic species.

Table 2-5 and Figures 2-9 through 2-13 show similar information for aromatic hydrocarbon content of samples. Table 2-6 contains the coefficients of correlation (r) for all sets of data.

Table 2-4
FIRST AND SECOND ANALYSES FOR NON-AROMATIC HYDROCARBONS (ppmv)

Sample	1st C1	2nd C1	Diff.	1st C2	2nd C2	Diff.	1st C3	2nd C3	Diff.	1st C4	2nd C4	Diff.	1st C5	2nd C5	Diff.	1st C6+	2nd C6+	Diff.
1	7	8	7%	1	1	0%	3	3	-9%	3	3	-6%	5	5	-2%	11	12	3%
2	2,275	2,390	5%	240	250	4%	355	357	1%	225	224	0%	74	71	-4%	30	17	-45%
3	69	72	5%	9	10	1%	8	8	1%	6	7	17%	6	5	-6%	6	4	-20%
4	70	72	3%	22	22	-2%	35	36	1%	14	13	-3%	7	6	-10%	4	4	-4%
5	4,488	4,633	3%	411	na		103	na		3	na		2	na		3	na	
6	89,800	92,600	3%	14,300	na		14,000	na		6,240	na		2,100	na		1,290	na	
7	3	3	3%	238	238	0%	30,100	31,200	4%	344	329	-4%	12	12	1%	4	4	8%
8	449	461	3%	39	39	0%	78	77	-1%	50	48	-3%	13	11	-19%	11	11	-4%
9	5,012	5,137	2%	456	na		191	na		66	na		32	na		26	na	
10	306	313	2%	45	46	2%	56	56	1%	21	21	-2%	14	11	-19%	15	15	1%
11	26,800	27,300	2%	50	49	-1%	1	2	6%	1	1	0%	1	1	0%	1	1	0%
12	21,900	22,300	2%	2,070	na		634	na		375	na		122	na		52	na	
13	4,400	4,480	2%	9	na		1	na		1	na		1	na		1	na	
14	498	507	2%	66	67	3%	129	132	2%	111	113	2%	56	58	3%	19	20	4%
15	303,000	307,000	1%	18,100	18,300	1%	6,740	7,100	5%	3,690	3,900	6%	1,460	1,520	4%	847	752	-11%
16	5	5	1%	2	1	-33%	7	7	-2%	9	8	-6%	3	3	5%	5	5	-3%
17	6,760	6,820	1%	954	na		241	na		101	na		32	na		19	na	
18	29,514	29,769	1%	3,109	na		5,290	na		3,536	na		1,490	na		805	na	
19	270	272	1%	28	28	-1%	36	38	3%	20	na		7	7	-6%	9	14	60%
20	540,000	544,000	1%	16,500	na		308	na		196	198	1%	28	na		4	na	
21	2,159	2,174	1%	254	257	1%	360	366	2%	196	198	1%	66	66	1%	28	30	7%
22	7,440	7,490	1%	336	328	-2%	141	137	-3%	87	85	-2%	36	35	-3%	21	21	-3%
23	551	554	1%	2,720	2,530	-7%	462	464	0%	71	71	0%	9	10	10%	1	1	47%
24	188,000	189,000	1%	54,600	na		27,800	na		8,220	na		1,840	na		274	na	
25	256,000	257,000	0%	54,400	na		37,500	na		11,000	na		2,640	na		445	na	
26	815,000	818,000	0%	59,800	na		15,700	na		3,970	na		1,180	na		274	na	
27	3	3	0%	1	1	15%	1	1	-8%	12	12	-2%	702	698	-1%	318	316	-1%
28	576,000	578,000	0%	966	na		31	na		4	na		2	na		1	na	
29	30	30	0%	3	3	-16%	10	5	-53%	4	3	-8%	4	3	-17%	8	8	5%
30	341,000	342,000	0%	21,000	na		5,550	na		2,240	na		1,100	na		554	na	
31	963,000	964,000	0%	1,740	na		44	na		8	na		9	na		4	na	
32	114	114	0%	10	10	1%	3	5	42%	1	1	9%	0.1	0.1	0.0	0.02	0.02	0%
33	375,000	375,000	0%	8,090	7,900	-2%	352	357	1%	44	44	0%	11	11	2%	3	3	-3%
34	1,710	1,710	0%	87	86	-1%	39	38	-4%	19	18	-5%	8	7	-6%	7	6	-5%
35	180	180	0%	27	26	-2%	11	11	-2%	21	21	-1%	32	31	-1%	50	46	-9%
36	10,100	10,100	0%	1,030	1,030	0%	328	323	-2%	46	44	-3%	5	5	1%	2	2	-13%
37	20,924	20,924	0%	1,785	1,785	0%	374	374	0%	1	na		3	na		7	na	
38	134,000	134,000	0%	3,450	3,260	-6%	64	na		1	na		0.1	na		0.4	na	

Table 2-4 (Continued)
FIRST AND SECOND ANALYSES FOR NON-AROMATIC HYDROCARBONS (ppmv)

Sample	1st C1	2nd C1	Diff.	1st C2	2nd C2	Diff.	1st C3	2nd C3	Diff.	1st C4	2nd C4	Diff.	1st C5	2nd C5	Diff.	1st C6+	2nd C6+	Diff.
39	2,220	2,220	0%	5	na		1	na		1	na		1	na		1	na	
40	267,000	267,000	0%	587	na		20	na		6	na		5	na		2	na	
41	865,000	864,000	0%	102,000	na		2,690	na		39	na		1	na		1	na	
42	82	82	0%	83	83	0%	117	117	0%	117	118	1%	68	69	3%	70	72	3%
43	36,500	36,400	0%	8,900	9,400	6%	3,930	4,070	4%	890	882	-1%	173	174	1%	30	31	4%
44	68,300	68,100	0%	645	na		30	na		2	na		0.02	na		na	na	
45	274,000	273,000	0%	56,500	na		37,000	na		12,000	na		2,500	na		411	na	
46	2,540	2,530	0%	98	99	1%	43	43	0%	26	26	-1%	8	9	14%	2	3	46%
47	23,500	23,400	0%	6,230	5,990	-4%	3,470	3,440	-1%	1,590	1,600	1%	656	634	-3%	244	234	-4%
48	41,700	41,500	0%	10,100	9,910	-2%	6,100	6,100	0%	2,860	2,900	1%	1,070	1,060	-1%	378	360	-5%
49	165	164	-1%	14	14	0%	4	4	-1%	2	2	-1%	1	1	-37%	0.2	0.04	-75%
50	4,770	4,740	-1%	49	48	-2%	3	2	-5%	0.1	na		ND	na		0.03	na	
51	146	145	-1%	2,700	2,740	1%	988	995	1%	145	148	2%	15	15	3%	12	10	-18%
52	42,800	42,500	-1%	287	na		8	na		1	na		0.4	na		ND	na	
53	2,600	2,580	-1%	94	na		3	na		0.3	na		1	na		2	na	
54	12,300	12,200	-1%	1,220	na		42	na		2	na		0.4	na		0.4	na	
55	245	243	-1%	30	29	-2%	56	58	3%	34	36	4%	12	12	0%	11	11	4%
56	242	240	-1%	27	27	-1%	43	44	2%	24	25	4%	6	7	9%	ND	ND	
57	113	112	-1%	3	3	-1%	1	1	-11%	2	2	8%	2	2	7%	1	1	8%
58	497	492	-1%	118	117	-1%	140	141	1%	89	90	1%	46	46	-1%	20	20	1%
59	6,820	6,750	-1%	419	na		132	na		52	na		11	na		5	na	
60	2,860	2,830	-1%	424	na		281	na		114	na		61	na		46	na	
61	17,900	17,700	-1%	174	na		80	na		38	na		31	na		15	na	
62	59,700	59,000	-1%	7,480	na		14,200	na		3,870	na		1,630	na		592	na	
63	32,700	32,300	-1%	13,600	na		24,500	na		9,410	na		2,090	na		376	na	
64	324	320	-1%	36	36	1%	34	27	-21%	12	12	3%	4	4	4%	3	3	1%
65	4,480	4,420	-1%	341	350	3%	21	21	2%	5	5	1%	0.2	0.1	-53%	0.02	ND	
66	21,900	21,600	-1%	669	na		20	na		1	na		1	na		1	na	
67	41,500	40,900	-1%	3,780	na		367	na		31	na		3	na		1	na	
68	73,100	72,000	-2%	510	508	0%	12	12	-1%	0.1	0.1	-2%	1	1	-4%	1	1	-10%
69	860	847	-2%	89	87	-3%	137	133	-3%	70	68	-3%	13	13	-1%	7	8	4%
70	262	258	-2%	111	115	4%	327	338	3%	413	420	2%	380	384	1%	440	455	3%
71	5	5	-2%	2	2	-19%	18	16	-7%	307	254	-17%	1,300	1,300	0%	334	336	1%
72	8	8	-2%	1	1	-21%	22	21	-1%	1,490	1,490	0%	9	8	-14%	3	3	-8%
73	152	149	-2%	65	64	-1%	232	232	0%	318	317	0%	296	290	-2%	360	359	0%
74	1,430	1,400	-2%	64	63	-2%	22	21	-3%	11	11	-3%	4	4	-7%	2	2	-22%
75	37	37	-2%	10	10	-2%	12	12	-2%	20	20	-2%	26	23	-9%	31	29	-4%
76	94,036	91,707	-2%	10,447	9,963	-5%	17,492	16,364	-6%	12,811	11,381	-11%	4,742	4,138	-13%	1,793	na	

Table 2-4 (Continued)
FIRST AND SECOND ANALYSES FOR NON-AROMATIC HYDROCARBONS (ppmv)

Sample	1st C1	2nd C1	Diff.	1st C2	2nd C2	Diff.	1st C3	2nd C3	Diff.	1st C4	2nd C4	Diff.	1st C5	2nd C5	Diff.	1st C6 +	2nd C6 +	Diff.
77	405	393	-3%	25	25	0%	42	42	-1%	31	31	1%	13	15	14%	9	10	15%
78	97	95	-3%	70	63	-2%	100	94	-6%	80	78	-3%	39	38	-2%	14	14	2%
79	1,640	1,590	-3%	177	179	1%	92	93	1%	41	42	1%	15	16	2%	8	8	1%
80	5	5	-4%	0.4	1	150%	36	36	1%	857	866	1%	1	2	47%	2	3	7%
81	7,220	6,920	-4%	240	na		77	na		38	na		16	na		10	na	
82	29	28	-4%	2	1	-12%	2	2	-5%	1	1	-2%	0.04	0.03	-25%	0.03	na	
83	64	61	-5%	20	20	-1%	26	25	-3%	27	27	-1%	18	17	-2%	22	22	-2%
84	6,350	6,010	-5%	1,030	977	-5%	453	na		212	na		64	na		21	na	
85	53	50	-6%	24	23	-3%	104	102	-2%	175	174	-1%	183	184	1%	230	224	-3%
86	4,500	4,240	-6%	160	160	0%	51	51	-1%	25	25	0%	9	11	20%	4	6	39%
87	13	12	-7%	57	57	-1%	295	292	-1%	364	360	-1%	203	202	0%	91	92	0%
88	15,900	14,700	-8%	154	na		7	na		0.04	na		ND	na		1	na	
89	3,088	2,853	-8%	253	na		85	na		1	na		5	na		8	na	
90	281	251	-11%	24	24	0%	8	8	0%	4	4	0%	2	1	-26%	2	1	-12%
91	60	50	-17%	25	25	-1%	38	38	0%	33	33	1%	16	17	5%	18	19	6%
92	4	3	-21%	42	41	-1%	77	76	-2%	37	36	-1%	11	11	-2%	6	5	-2%
93	29	22	-23%	7	7	-2%	13	13	6%	22	24	8%	34	37	9%	51	56	9%
94	4	3	-25%	11	11	3%	75	73	-2%	187	185	-1%	95	93	-1%	11	15	37%
95	193	129	-33%	7	6	-26%	0.2	0.2	-30%	ND	ND		0.3	0.3	0.1	0.3	0.3	-9%
96	531,000	na		873	877	0%	22	22	0%	4	4	-3%	2	1	-32%	1	1	1%
97	369,000	na		667	672	1%	14	16	15%	3	4	22%	3	3	-4%	1	1	0%
98	275,000	na		490	500	2%	10	10	-1%	1	2	15%	2	2	33%	1	1	0%
99	250,000	na		113,000	102,000	-10%	41,800	37,600	-10%	13,100	12,500	-5%	3,670	3,580	-2%	1,960	na	
100	36,823	na		3,561	3,268	-8%	4,489	4,045	-10%	2,928	2,545	-13%	1,534	1,268	-17%	1,279	1,025	-20%
101	28,600	na		3,830	3,700	-3%	5,050	4,880	-3%	1,870	1,790	-4%	621	598	-4%	169	165	-2%
102	19,600	na		1,200	1,280	7%	375	402	7%	154	164	6%	69	74	6%	39	41	5%
103	12,700	na		5,370	5,400	1%	4,920	4,390	-11%	3,500	3,500	0%	1,680	1,690	1%	518	528	2%
104	8,367	na		711	738	4%	1,028	1,035	1%	571	574	1%	231	225	-3%	113	101	-11%
105	3,806	na		321	305	-5%	619	592	-4%	494	389	-21%	100	88	-12%	67	na	
106	2,880	na		322	321	0%	93	93	0%	26	26	0%	8	9	0%	6	6	-2%
107	2,220	na		109	110	1%	17	17	0%	3	3	1%	1	1	-41%	15	14	-9%
108	1,530	na		307	307	0%	473	472	0%	357	356	0%	150	150	0%	66	66	0%
109	1,330	na		59	59	-1%	26	26	0%	17	17	-2%	9	8	-12%	6	5	-17%

ND = Not detected
na = Not analyzed

Figure 2-3. COMPARISON OF REPEAT ANALYSES AT LABORATORY C1

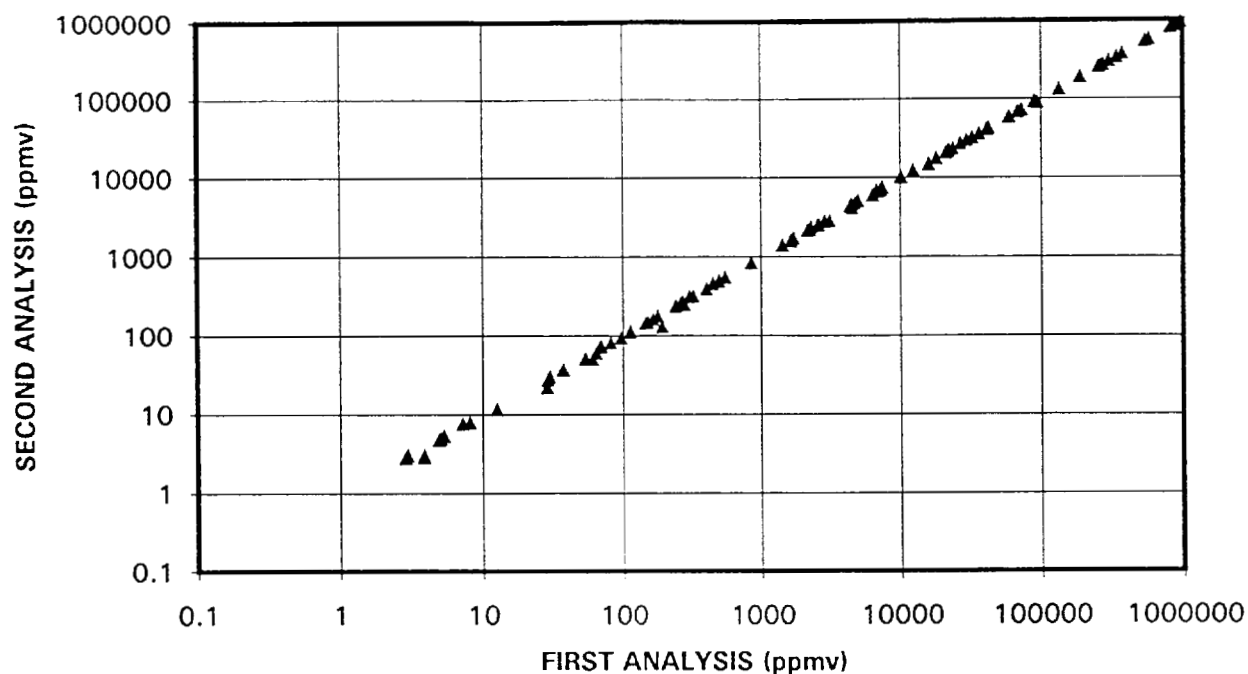


Figure 2-4. COMPARISON OF REPEAT ANALYSES AT LABORATORY C2

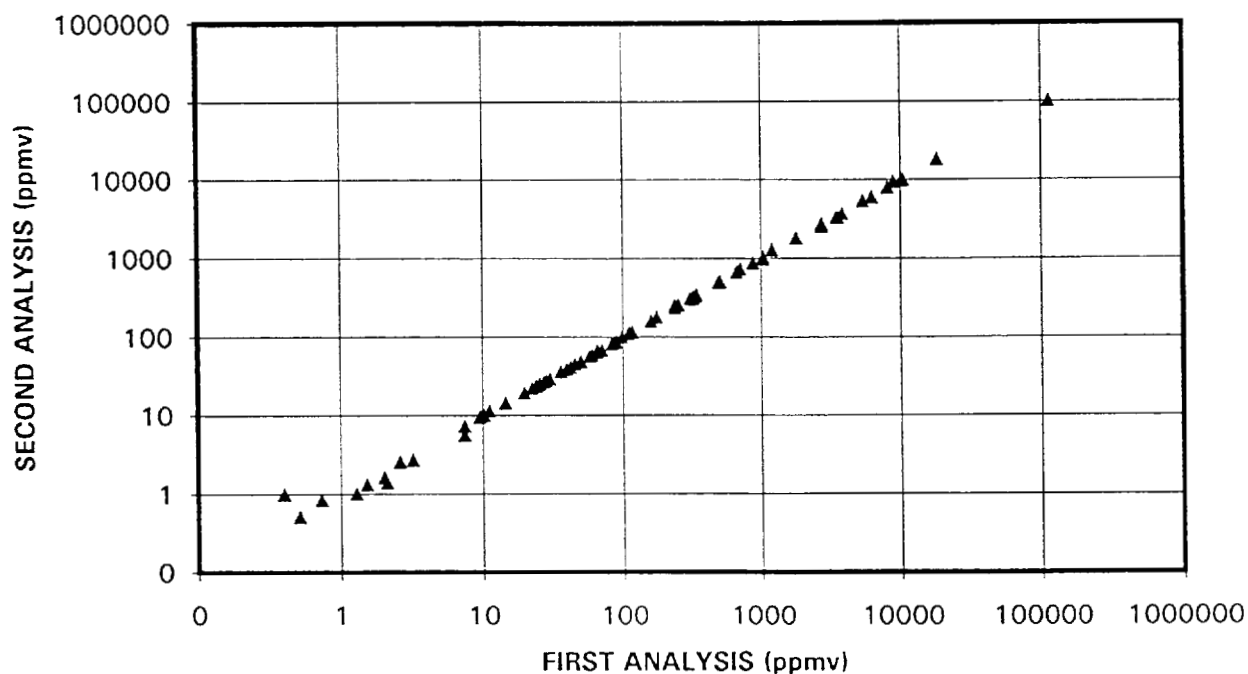


Figure 2-5. COMPARISON OF REPEAT ANALYSES AT LABORATORY C3

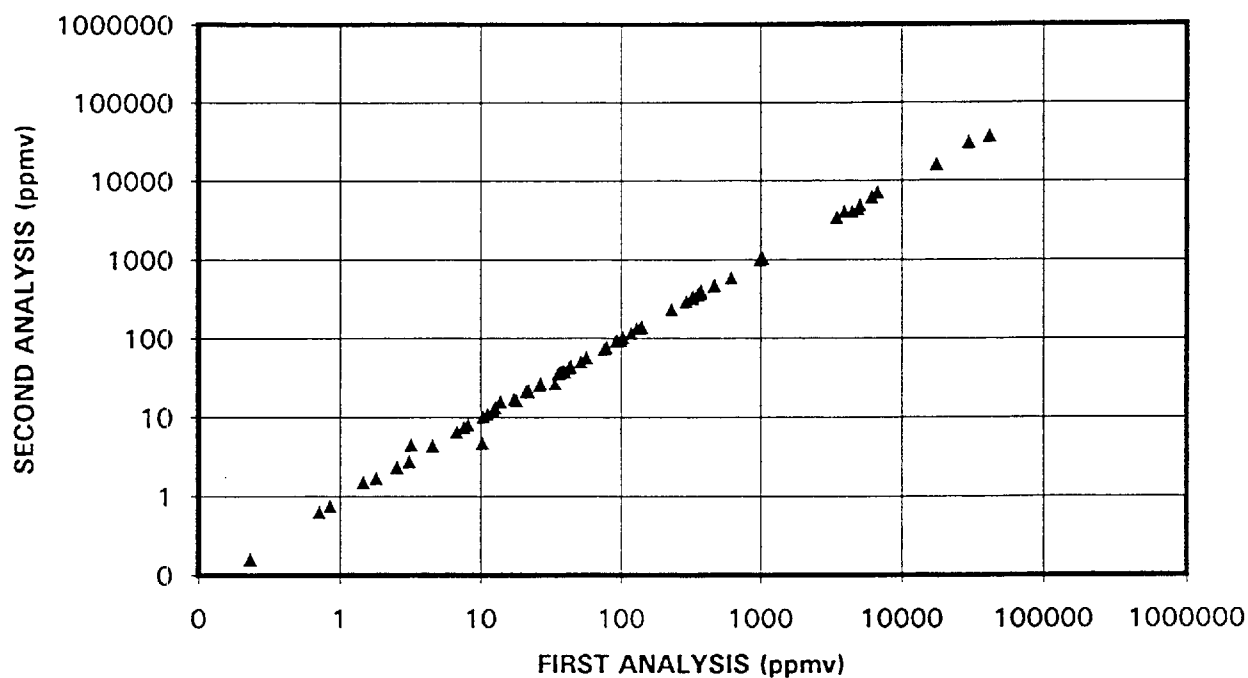


Figure 2-6. COMPARISON OF REPEAT ANALYSES AT LABORATORY C4

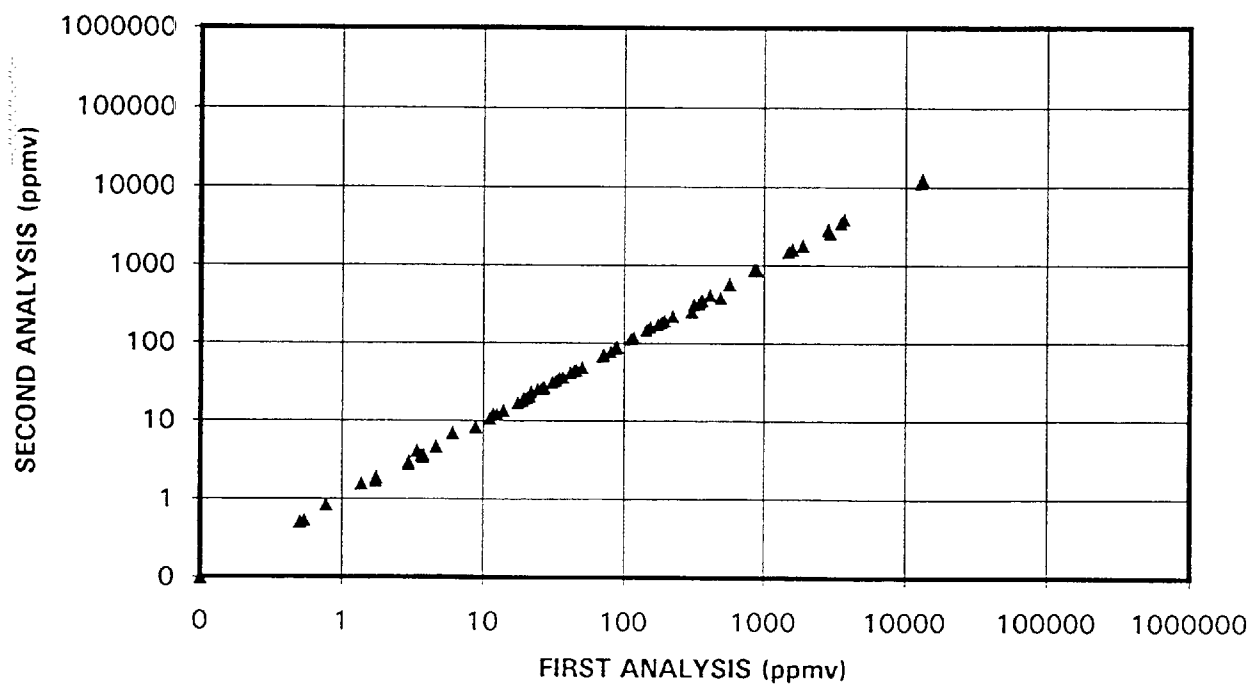


Figure 2-7. COMPARISON OF REPEAT ANALYSES AT LABORATORY C-5

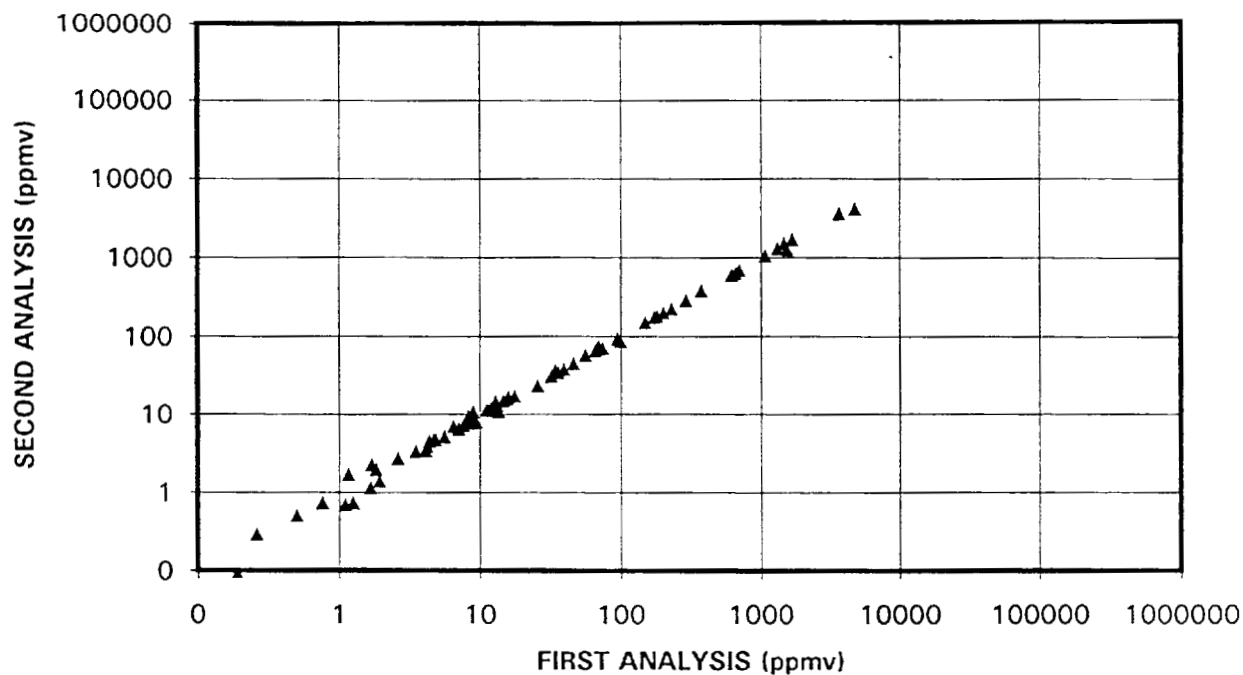


Figure 2-8. COMPARISON OF REPEAT ANALYSES AT LABORATORY C6+

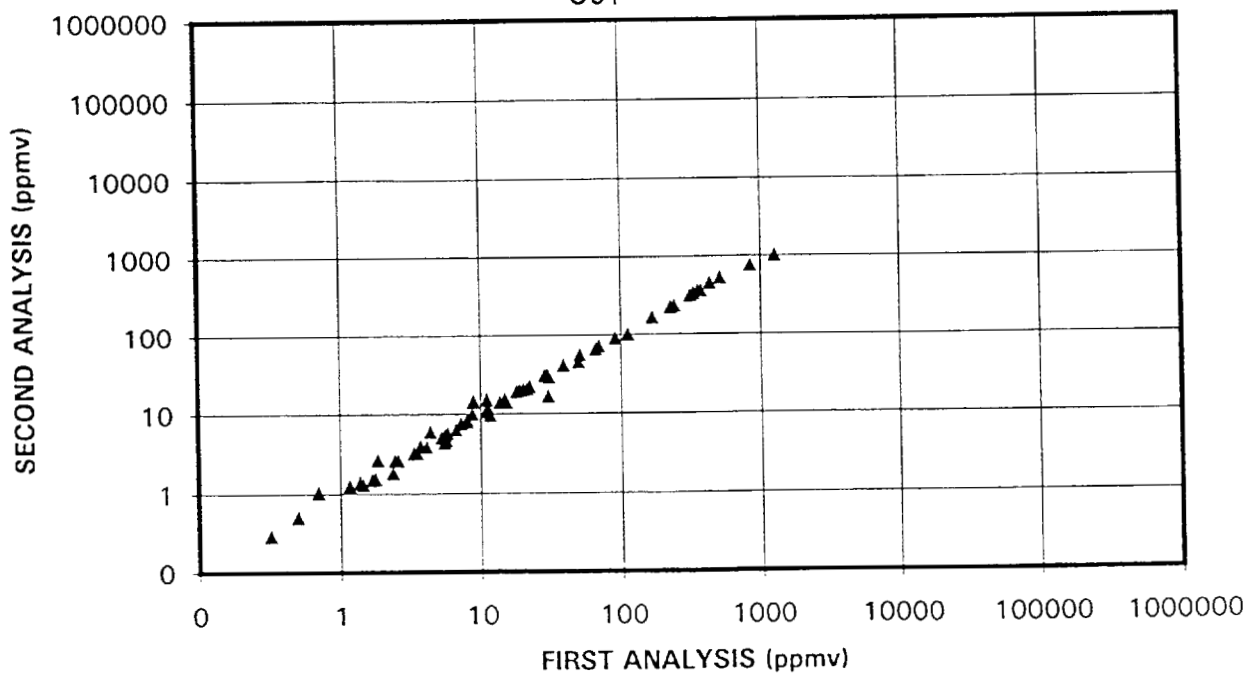


Table 2-5
FIRST AND SECOND ANALYSES FOR AROMATIC HYDROCARBONS (ppmv)

Sample	Benzene 1	Benzene 2	Diff.	Toluene 1	Toluene 2	Diff.	E-Ben1	E-Ben2	Diff.	m + p Xyl1	m + p Xyl2	Diff.	o Xyl1	o Xyl2	Diff.
A	0.039	0.028	28%	0.075	0.075	0%	0.020	0.020	0%	0.020	0.020	0%	0.020	0.020	0%
B	0.399	0.354	11%	0.544	0.542	0%	0.142	0.157	-11%	0.154	0.181	-18%	0.083	0.080	4%
C	0.128	0.114	11%	0.779	0.712	9%	0.217	0.182	16%	0.325	0.250	23%	5.400	5.160	4%
D	0.231	0.210	9%	0.085	0.095	-12%	0.065	0.065	0%	0.065	0.065	0%	0.065	0.065	0%
E	17.600	16.100	9%	1.520	1.490	2%	0.244	0.240	2%	0.250	0.235	6%	0.095	0.109	-15%
F	5.390	5.030	7%	5.960	5.580	6%	0.144	0.097	32%	0.207	0.145	30%	0.065	0.065	0%
G	3.190	3.030	5%	1.590	1.540	3%	0.055	0.055	0%	0.103	0.092	11%	0.055	0.055	0%
H	80.000	76.800	4%	4.370	4.340	1%	0.095	0.118	-24%	0.904	0.757	16%	0.500	0.500	0%
I	0.180	0.173	4%	0.302	0.318	-5%	0.055	0.055	0%	0.117	0.133	-14%	0.055	0.055	0%
J	1.810	1.750	3%	1.760	1.720	2%	0.055	0.055	0%	0.217	0.231	-6%	0.055	0.055	0%
K	1.750	1.700	3%	4.240	4.280	-1%	0.205	0.178	13%	1.140	1.230	-8%	0.362	0.367	-1%
L	2.400	2.340	3%	1.040	0.998	4%	0.055	0.055	0%	ND	ND		0.055	0.055	0%
M	12.200	11.900	2%	4.220	4.680	-11%	0.060	0.060	0%	0.096	0.075	22%	0.050	0.050	0%
N	4.970	4.870	2%	7.360	7.220	2%	0.200	0.138	31%	1.040	0.990	5%	ND	ND	
O	2.140	2.110	1%	0.307	0.305	1%	0.020	0.020	0%	ND	ND		0.020	0.020	0%
P	4.360	4.310	1%	8.540	8.440	1%	ND	ND		ND	ND		ND	ND	
Q	1.870	1.860	1%	4.080	4.080	0%	0.306	0.271	11%	0.710	0.654	8%	0.347	0.322	7%
R	42.500	42.300	0%	16.200	16.600	-2%	0.905	0.830	8%	0.963	0.973	-1%	0.430	0.324	25%
S	0.534	0.532	0%	1.840	1.810	2%	0.072	0.077	-7%	0.619	0.566	9%	0.167	0.142	15%
T	0.065	0.065	0%	0.107	0.093	13%	0.065	0.065	0%	0.065	0.065	0%	0.065	0.065	0%
U	0.035	0.035	0%	na	na		na	na		na	na		na	na	
V	0.035	0.035	0%	na	na		na	na		na	na		na	na	
W	0.248	0.249	0%	0.741	0.725	2%	0.023	0.025	-10%	0.097	0.102	-5%	0.035	0.042	-19%
X	5.690	5.730	-1%	0.424	0.430	-1%	0.050	0.050	0%	0.080	0.080	0%	0.050	0.050	0%
Y	2.240	2.270	-1%	6.500	6.540	-1%	0.408	0.420	-3%	2.240	2.020	10%	0.586	0.590	-1%
Z	5.400	5.500	-2%	14.100	14.700	-4%	1.090	1.180	-8%	1.660	1.710	-3%	ND	ND	
AA	0.477	0.486	-2%	1.060	1.060	0%	0.189	0.190	-1%	0.268	0.274	-2%	0.135	0.141	-4%
BB	7.130	7.280	-2%	5.330	5.320	0%	0.656	0.548	16%	1.210	1.060	12%	0.350	0.474	-35%
CC	3.360	3.440	-2%	10.500	11.000	-5%	0.703	0.723	-3%	2.730	2.940	-8%	1.140	1.050	8%

ND = Not detected. na = Not analyzed.

Figure 2-9. COMPARISON OF REPEAT ANALYSES AT LABORATORY
(Benzene)

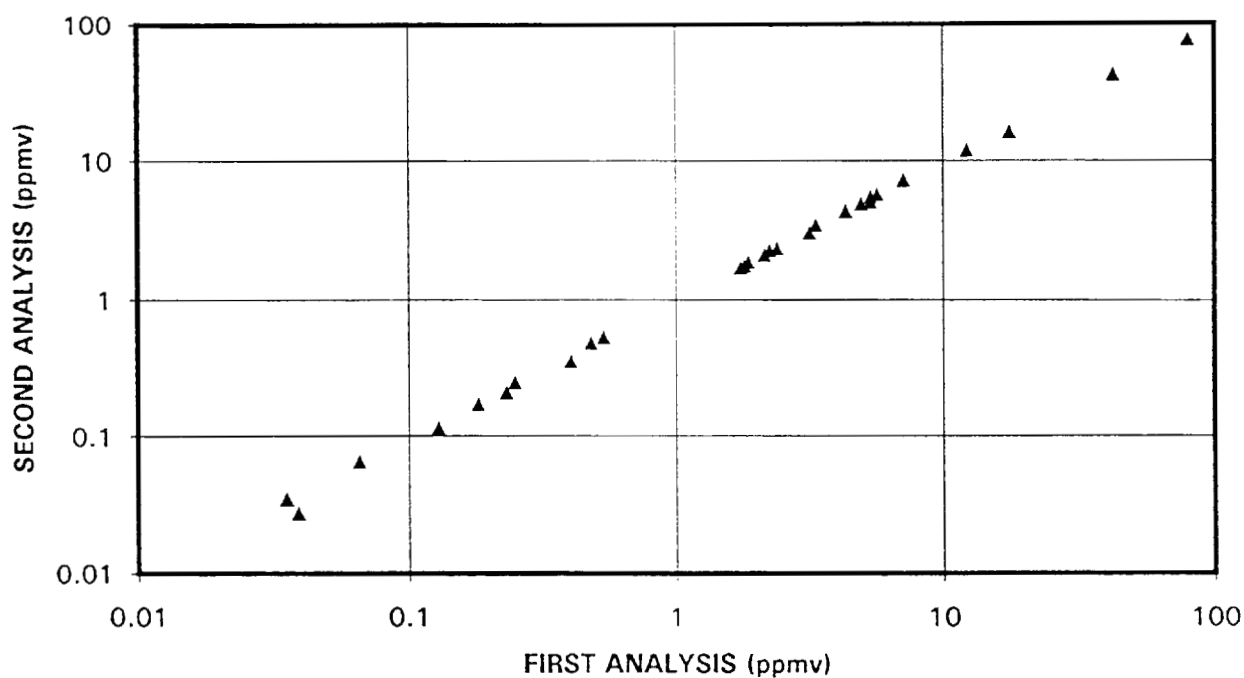


Figure 2-10. COMPARISON OF REPEAT ANALYSES AT LABORATORY
(Toluene)

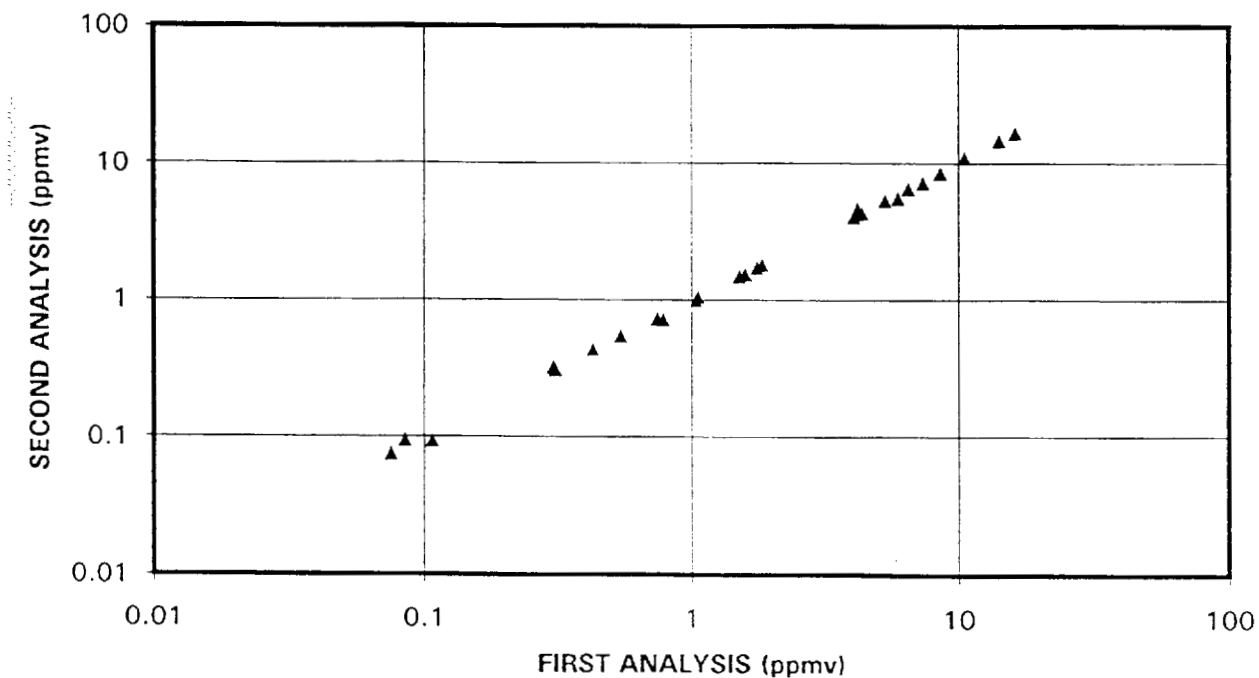


Figure 2-11. COMPARISON OF REPEAT ANALYSES AT LABORATORY
(Ethyl Benzene)

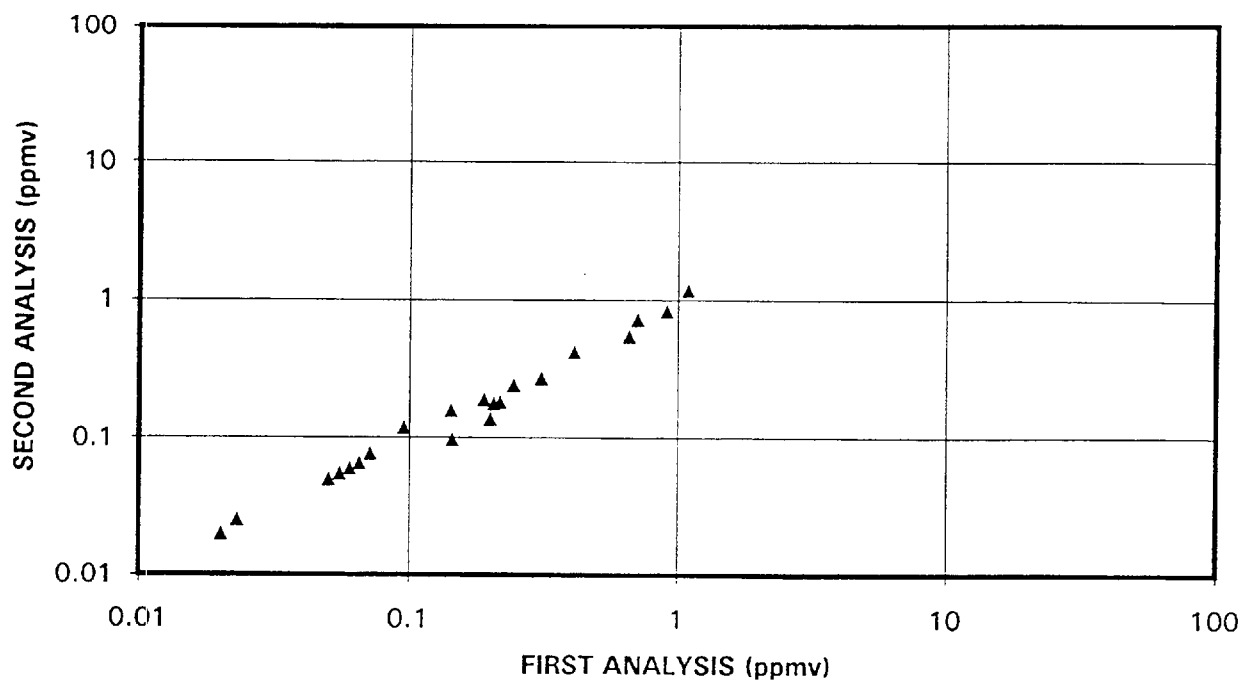


Figure 2-12. COMPARISON OF REPEAT ANALYSES AT LABORATORY
(m + p Xylene)

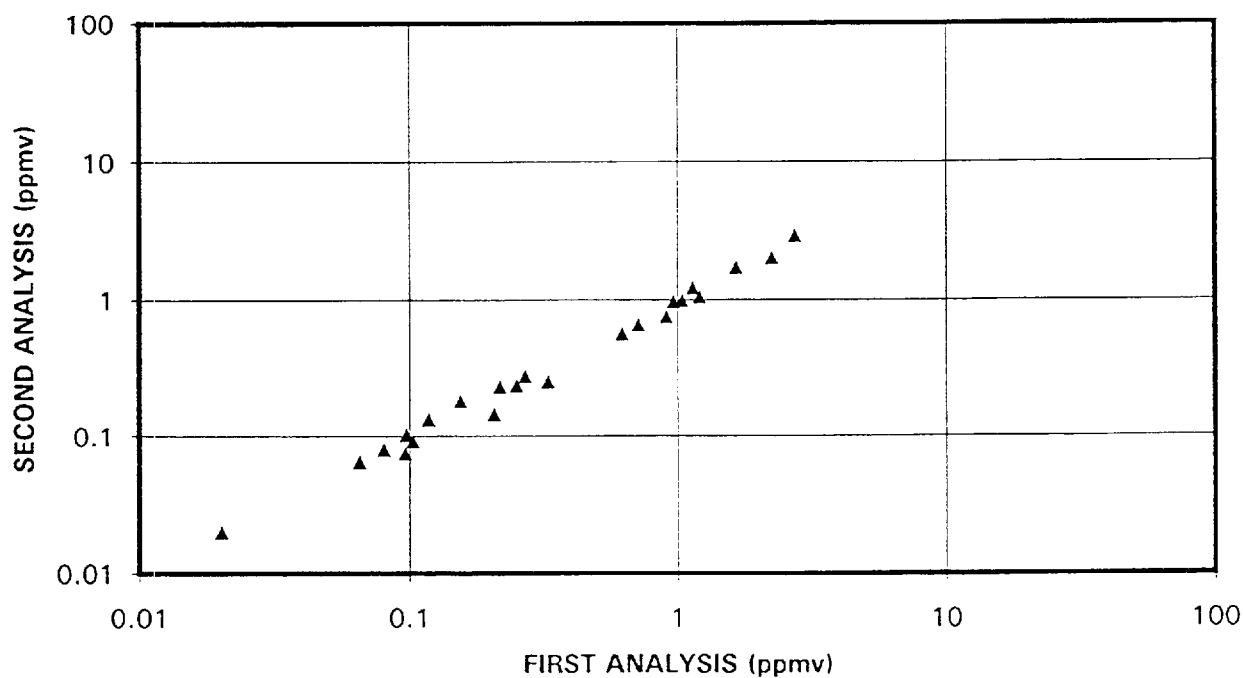


Figure 2-13. COMPARISON OF REPEAT ANALYSES AT LABORATORY
(o Xylene)

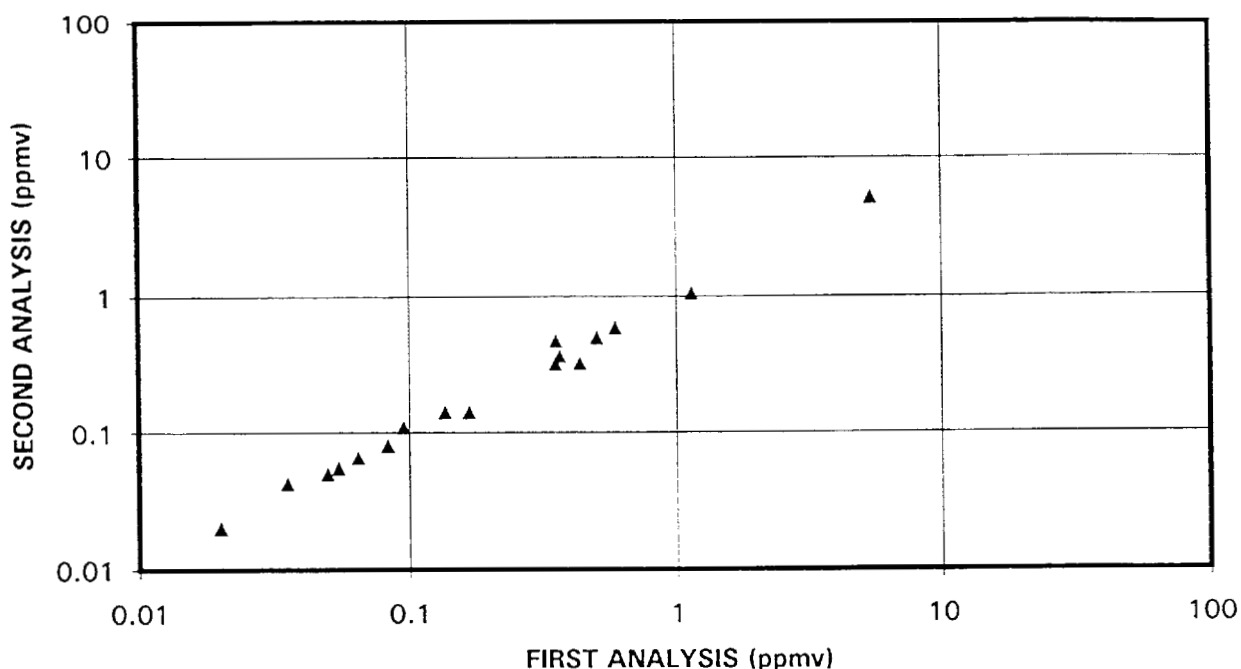
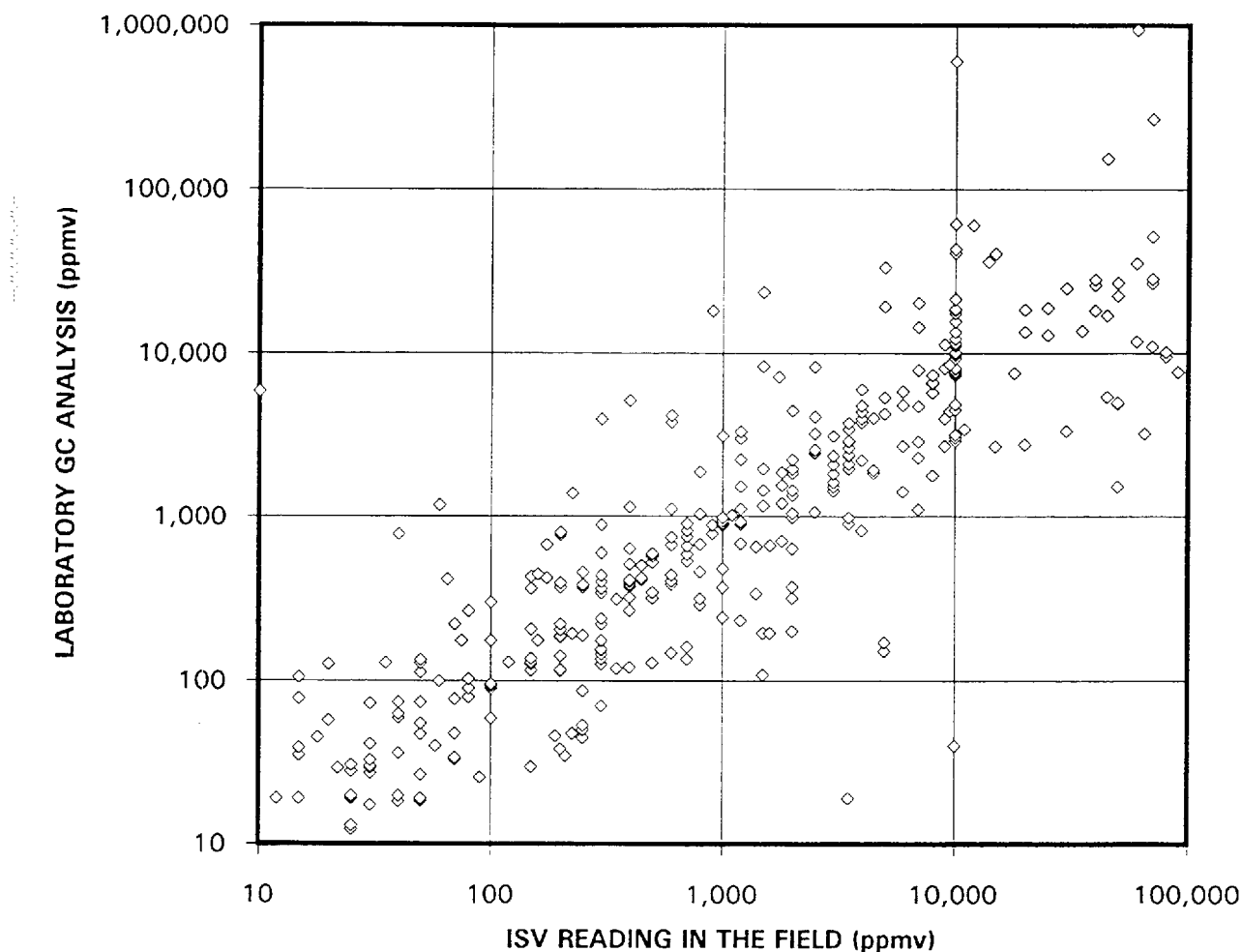


Table 2-6. CORRELATION OF REPEATED LABORATORY ANALYSES

CHEMICAL SPECIES	COEFFICIENT OF CORRELATION (r)
Methane	0.99983
C2 hydrocarbons	0.99880
C3 hydrocarbons	0.99803
C4 hydrocarbons	0.99971
C5 hydrocarbons	0.99645
C6+ hydrocarbons	0.99485
Benzene	0.99950
Toluene	0.99927
Ethyl Benzene	0.99947
m+p Xylenes	0.99545
o Xylene	0.99692

Monitoring instruments were calibrated daily with certified concentrations of methane in air. During sample collection, the pump outlet was measured with the monitoring instrument just before filling the sample bag to give "as filled" ISVs. As an additional check on accuracy of the field crew, bagging techniques, and sample collection procedures, the "as filled" ISVs of the sample bags were compared with the "as analyzed" concentrations (see Figure 2-14). The coefficient of correlation for these data is: $r = 0.86$. This indicates that calibration procedures, bagging procedures, and sampling procedures produced acceptable results.

Figure 2-14. COMPARISON OF ONSHORE SAMPLE BAGS
AS COLLECTED AND AS ANALYZED
(Total Hydrocarbons)



CORRELATION EQUATIONS

Correlation equations were developed to predict mass emission rates for ISVs above 10 ppmv. World-wide background levels of methane approach 2 ppmv in open areas; localized areas such as swamps, highways, farms, and industrial sites often have background concentrations exceeding 5 ppmv. Therefore, it is inadvisable to attempt to measure ISVs less than 10 ppmv and/or use correlation equations to predict emissions from these extremely small sources. Sources with ISVs less than 10 ppmv were assumed to have ISVs of 5 ppmv.

All measured ISVs were used to produce the correlation equations that were developed by regressing the natural logarithm of total hydrocarbon emissions on the natural logarithm of ISV. The analysis

began with a general Analysis of Variance (ANOVA) model that allowed for four types of components with the possibility of different intercepts and different slopes for each component type. Terms not statistically significant were excluded sequentially from the model until all terms left in the model were significant. The resulting correlation equations are shown in Table 2-7.

Table 2-7. CORRELATION EQUATIONS

FACILITY TYPE	COMPONENT TYPE	CORRELATION EQUATION
Onshore Light Crude	CN, VL, OEL	$\text{THC}(\text{lb/day}) = 8.61 \times 10^{-5}(\text{ISV ppmv})^{0.83}$
Onshore Light Crude	Other	$\text{THC}(\text{lb/day}) = 1.24 \times 10^{-3}(\text{ISV ppmv})^{0.61}$
Onshore Heavy Crude	All	$\text{THC}(\text{lb/day}) = 3.29 \times 10^{-5}(\text{ISV ppmv})^{0.89}$
Onshore Gas Production	CN, OEL	$\text{THC}(\text{lb/day}) = 8.04 \times 10^{-6}(\text{ISV ppmv})^{1.02}$
Onshore Gas Production	VL, Other	$\text{THC}(\text{lb/day}) = 9.79 \times 10^{-5}(\text{ISV ppmv})^{0.96}$
Onshore Gas Plant	All	$\text{THC}(\text{lb/day}) = 1.79 \times 10^{-4}(\text{ISV ppmv})^{0.87}$

Figures 2-15 through 2-20 show the total hydrocarbon (THC) emissions data and correlation equations in log-log plots for each facility type/component type combination. Note that most individual data points fall below the correlation lines. This is due to the nature of log-log plots.

Figure 2-15. LIGHT CRUDE PRODUCTION CORRELATION
(CN,VL, OEL)

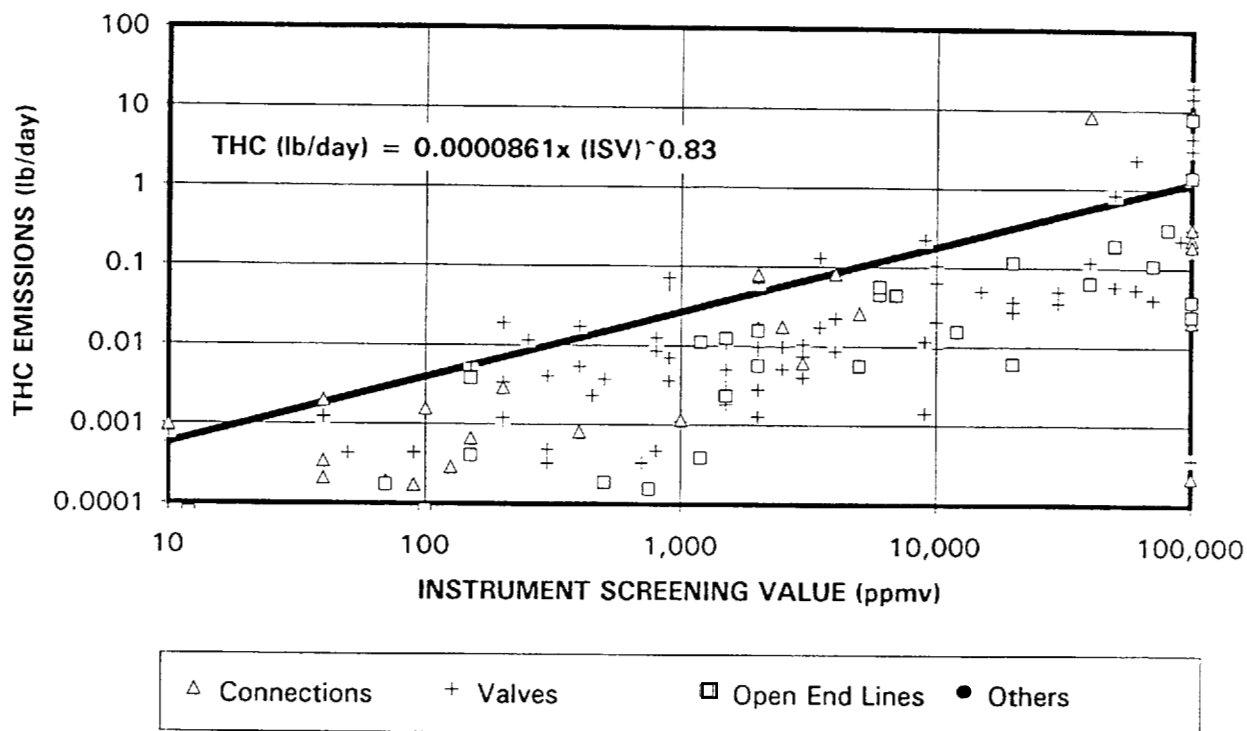


Figure 2-16. LIGHT CRUDE PRODUCTION CORRELATION
(Others)

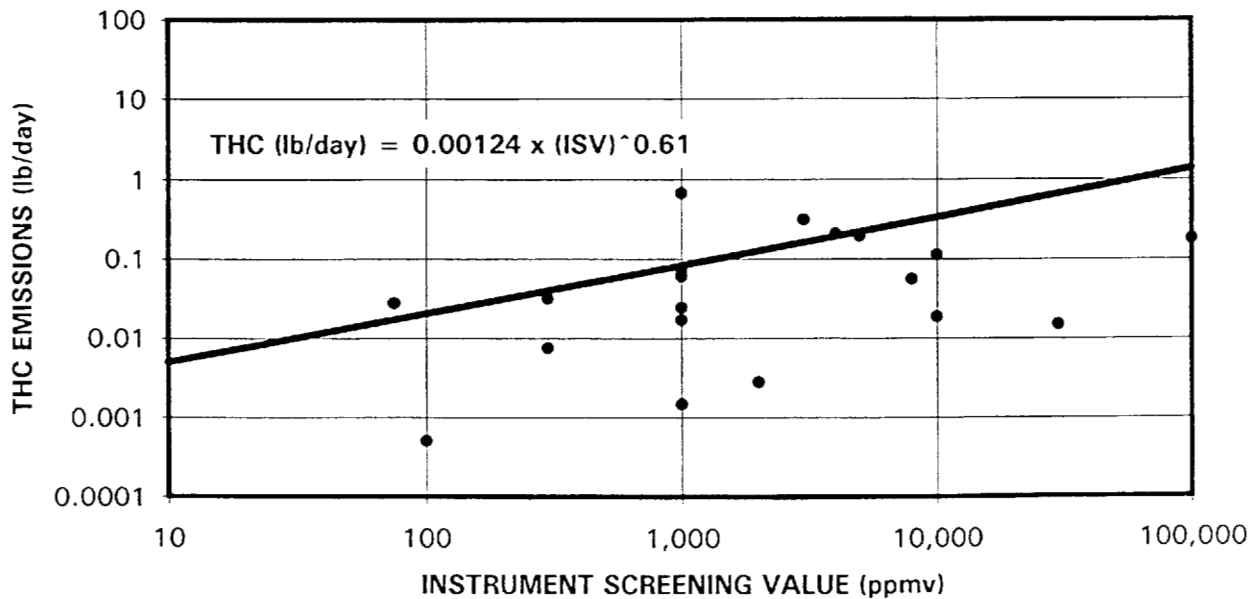


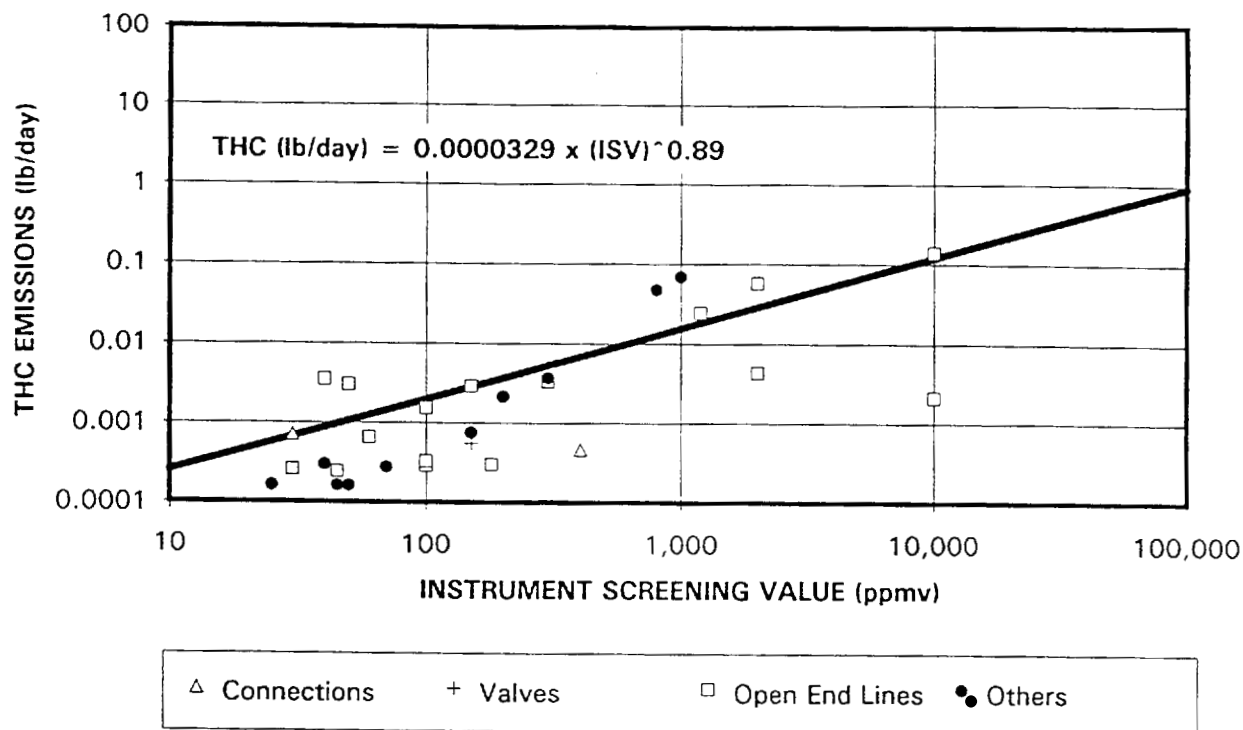
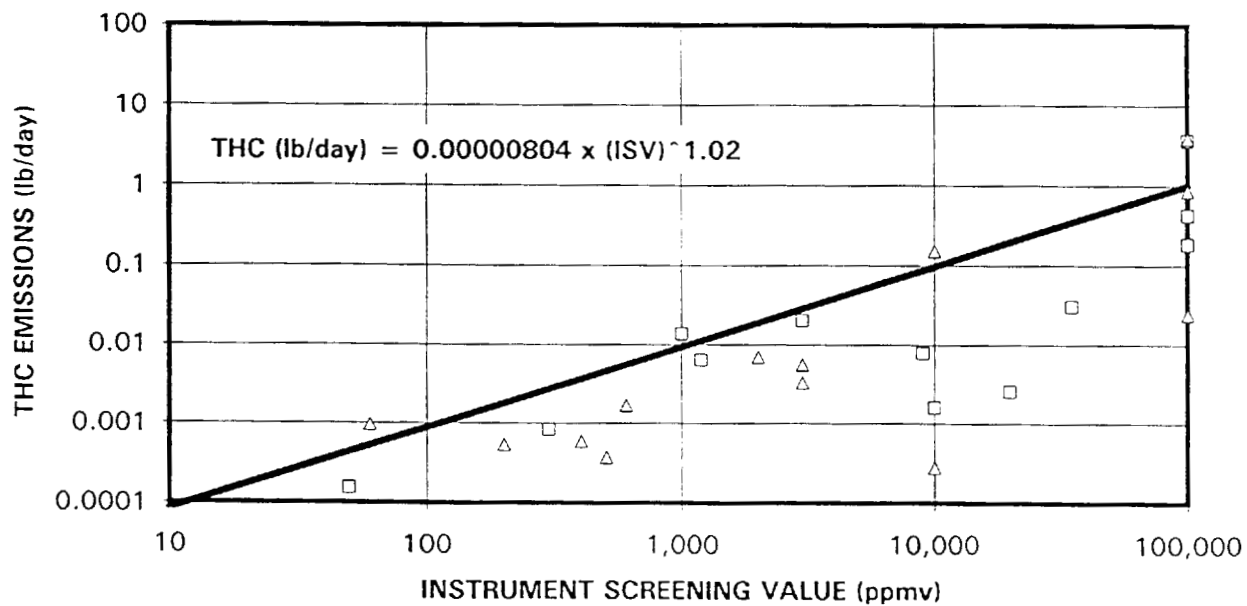
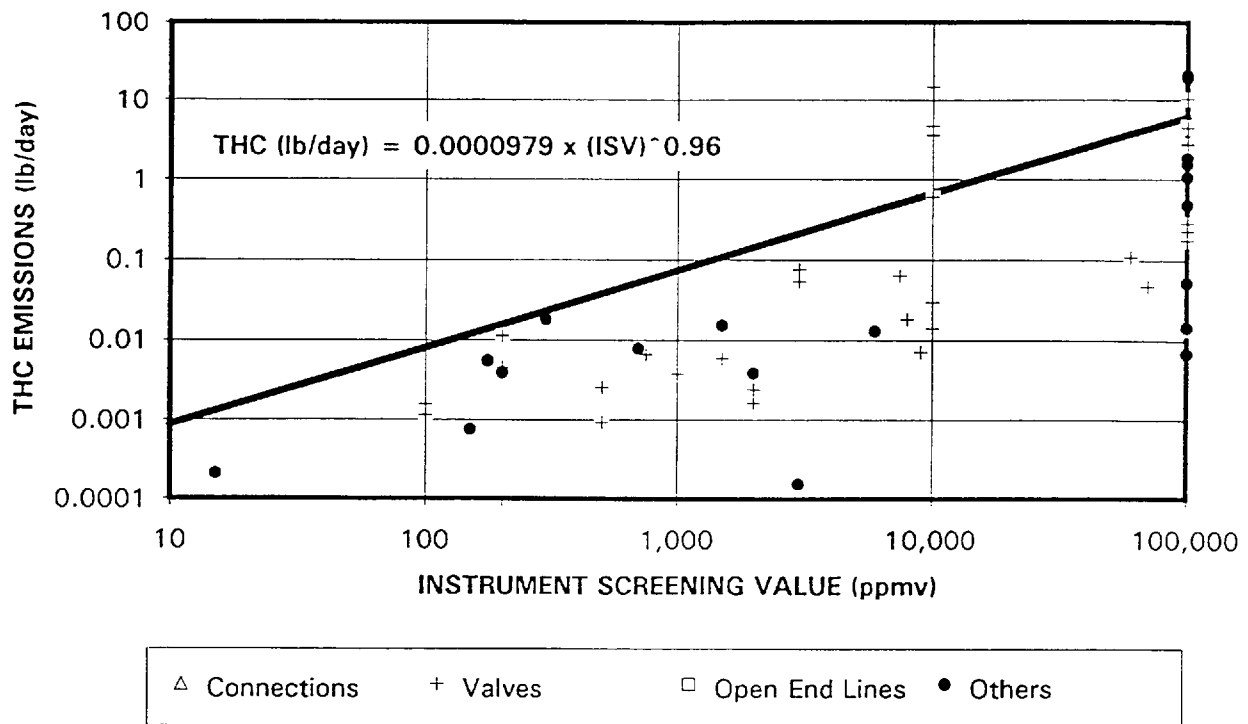
Figure 2-17. HEAVY CRUDE PRODUCTION CORRELATION
(CN, VL, OEL, Others)Figure 2-18. NATURAL GAS PRODUCTION CORRELATION
(CN, OEL)

Figure 2-19. NATURAL GAS PRODUCTION CORRELATION
(VL, Others)Figure 2-20. NATURAL GAS PROCESSING CORRELATION
(CN, VL, OEL, Others)