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HM 65

Atmospheric hydrocarbon emissions from marine vessel transfer operations

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Atmospheric hydrocarbon emissions from marine vessel transfer operations

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Foreword

This publication was prepared jointly by the American Petroleum Institute Committee on Petroleum Measurement and the Energy Institute Hydrocarbon Management Committee. This standard supersedes API Publication 2514A, Second Edition, September 1981, which is withdrawn. See A.1 for more information on the previous editions of this document.

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Atmospheric hydrocarbon emissions from marine vessel transfer operations

1 Scope

This standard provides methods for estimating evaporative loss from marine vessel transfer operations. Specifically, this standard addresses:

1) loading stock into:

    a) ship or ocean barges, or

    b) shallow draft barges, and

2) loading ballast water into ship or ocean barges from which crude oil has been unloaded.

The emission estimates are for uncontrolled loading operations and do not apply to operations using vapor balance or vapor control systems or ballasting of ships with segregated ballast tanks.

This standard does not address evaporative loss for:

1) very large crude carriers (VLCCs) or ultra large crude carriers (ULCCs) (unless the saturation factor K_S is determined);

2) marine vessels employing crude oil washing (see 3.3.1);

3) marine vessel transit loss;

4) loading ballast water into marine vessels that, prior to dockside unloading, held anything other than crude oil (unless the saturation factor K_S is determined); or

5) unloading marine vessels.

This standard supersedes API 2514A, Second Edition, September 1981, which is withdrawn.

2 References

[1] American Petroleum Institute, *Recommended Practice for Specification of Evaporative Losses*, *Manual of Petroleum Measurement Standards*, Chapter 19, Section 4, Second Edition, September 2005

[2] American Petroleum Institute, Publication 2524, *Impact Assessment of New Data on the Validity of American Petroleum Institute Marine Transfer Operation Emission Factors*, July 1992

[3] American Petroleum Institute, Publication 2514A, *Atmospheric Hydrocarbon Emissions from Marine Vessel Transfer Operations*, Second Edition, September 1981

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[7] Energy Institute, London, HM 40, *Guidelines for the Crude Oil Washing of Ships' Tanks and the Heating of Crude Oil Being Transported by Sea*, Second Edition, June 2004

[8] U.S. Environmental Protection Agency, 5.2.2.1 "Rail Tank Cars, Tank Trucks, and Marine Vessels," in *Compilation of Air Pollutant Emission Factors*, USEPA Report No. AP-42, January 1995

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[10] American Petroleum Institute, *Evaporative Loss from Fixed-roof Tanks*, *Manual of Petroleum Measurement Standards*, Chapter 19, Section 1, Third Edition, March 2002

[11] Western Oil and Gas Association, *Hydrocarbon Emissions During Marine Tanker Loading,* Measurement Program, Ventura County, California, May 1977

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3 Terms and Definitions

For the purposes of this document, the following definitions apply.

3.1 Marine Vessel Type

3.1.1
shallow draft barge
Marine vessels with compartment depths of approximately 10 ft to 12 ft.

3.1.2
ship or ocean barge
Marine vessels with compartment depths of approximately 40 ft.

3.2 Cargo Type

3.2.1
nonvolatile cargo
Cargo with a true vapor pressure of 1.5 psia or less. Nonvolatile cargo includes fuel oils such as No. 2 fuel oil (diesel) and No. 6 fuel oil.

3.2.2
volatile cargo
Cargo with a true vapor pressure greater than 1.5 psia.

3.3 Cargo Compartment Condition

3.3.1 Cargo Compartment Condition Prior to Loading

3.3.1.1
ballasted compartment
An uncleaned compartment that has been loaded with ballast water.

3.3.1.2
cleaned compartment
A compartment that has been water washed.

3.3.1.3
crude oil washing
The use of a high pressure stream of crude oil or cutter stock, usually heated, to dislodge or dissolve clingage and sediments from bulkheads, compartment bottoms, and internal structures of a vessel during the discharge operation. [7]

3.3.1.4
gas-freed compartment
A compartment that has been cleaned and air-blown, such that the compartment is suitable for entry and hot work such as welding.

3.3.1.5
uncleaned compartment
A compartment that has had no treatment except routine heel washing (washing restricted to the lower part of the compartment).

3.3.2 Cargo Compartment Condition Prior to Dockside Crude Oil Unloading

3.3.2.1
fully-loaded compartment
A compartment with a true ullage height of 5 ft or less prior to dockside crude oil unloading.

3.3.2.2
lightered or previously short-loaded compartment
A compartment with a true ullage of more than 5 ft prior to dockside crude oil unloading.

3.4 Miscellaneous Terminology

3.4.1
lightered
Partially unloaded before reaching the dock.

3.4.2
ullage
The unfilled volume of a compartment.

Table 1—Nomenclature

Symbol	USC Units	SI Units	Description
K_S	—	—	saturation factor
L_L	lb	kg	loading loss
M_V	lb/lb-mole	kg/kg-mole	molecular weight of the stock vapors (see API *MPMS* Ch.19.4 [1], Table 2)
P_{VA}	lb/in.^{2}	kPa	true vapor pressure of the liquid (see API *MPMS* Ch. 19.4 [1], Table 2)
R	lb-ft^3/(lb-mole °R-in.^{2})	l-atm/(g-mole K)	ideal gas constant = 10.731 lb-ft^3/(lb-mole °R-in.^{2}) ideal gas constant = 0.08206 l-atm/(g-mole K)
T_V	°R	K	absolute temperature of the ullage
V_L	ft^3, gal, or bbl	m^3 or l	volume of liquid loaded
W_V	lb/ft^3	kg/m^3	density of the stock vapors

4 Procedures for Estimating Loss

This section summarizes estimating loading losses. Further information on the development of the method is provided in Section 6.

4.1 Loading Loss

The loss from an uncontrolled petroleum liquid loading episode L_L developed in Section 6 is:

$$L_L = V_L K_S P_{VA} M_V /(RT_V) \quad (1)$$

where

V_L is the volume of liquid loaded;

K_S is the saturation factor (see Table 2);

P_{VA} is the true vapor pressure of the liquid;

M_V is the molecular weight of the stock vapors;

R is the ideal gas constant;

T_V is the absolute temperature of the ullage.

This equation can be written as (with the units as given in Table 1):

$$L_L \text{ lb/(1000 gal loaded)} = 12.46 K_S P_{VA} M_V /T_V \quad (2)$$

or

$$L_L \text{ kg /(1000 l loaded)} = 0.1203 K_S P_{VA} M_V /T_V \quad (3)$$

Table 2 shows that the loading loss saturation factor is a function of the compartment condition prior to loading. A barge may have more than one compartment and the compartments may have different conditions prior to loading.

Table 2—Loading Loss Saturation Factor K_S

Marine Vessel Type	Prior Cargo	Compartment Condition Prior to Loading	K_S (gasoline loading)	K_S (crude oil loading)	K_S (other petroleum liquids loading)
Ship or ocean barge	Volatile	Uncleaned	0.2	0.2	0.2
Ship or ocean barge	Volatile	Ballasted	0.15	0.15	—
Ship or ocean barge	Volatile	Cleaned	0.10	0.10	—
Ship or ocean barge	Volatile	Gas freed	0.10	0.10	—
Ship or ocean barge	Nonvolatile	Uncleaned, ballasted, cleaned, or gas freed	0.10	0.10	—
Shallow draft barge	Volatile	Uncleaned	0.3	0.3	0.5
Shallow draft barge	Volatile	Cleaned or gas freed	0.15	—	—
Shallow draft barge	Nonvolatile	Uncleaned, cleaned, or gas freed	0.15	—	—

4.2 Ballasting Loss

The loss for an uncontrolled ballast water loading episode L_L is the same as for petroleum liquid loading, but with the variables as defined below:

$$L_L = V_L K_S P_{VA} M_V /(RT_V) \tag{4}$$

where

- V_L is the volume of the ballast water loaded into compartments that previously contained crude oil. If the volume is unknown, it can be estimated as 17 % of the volume of the crude oil unloaded;
- K_S is the saturation factor (see Table 3);
- P_{VA} is the true vapor pressure of the crude oil unloaded;
- M_V is the vapor molecular weight of the crude oil unloaded;
- R is the ideal gas constant;
- T_V is the absolute temperature of the ullage.

This equation can be written as:

$$L_L \text{ lb/(1000 gal loaded)} = 12.46\, K_S P_{VA} M_V /T_V \tag{2}$$

or

$$L_L \text{ kg /(1000 l loaded)} = 0.1203\, K_S P_{VA} M_V /T_V \tag{3}$$

Like Table 2, Table 3 shows that the ballasting loss saturation factor is a function of the compartment condition prior to loading. A barge may have more than one compartment and the compartments may have different conditions prior to loading.

Table 3—Ballasting Loss Saturation Factor K_S

Marine Vessel Type	Prior Cargo	Compartment Condition Prior to Dockside Crude Oil Unloading	K_S
Ship or ocean barge	Crude oil	Fully loaded	0.20
Ship or ocean barge	Crude oil	Lightered or previously short loaded	0.35

5 Sample Problems

5.1 Loss from Loading Gasoline

5.1.1 Parameters

Marine vessel: ocean barge.

Prior cargo: volatile.

Compartment conditions prior to loading: 25 % uncleaned, 10 % ballasted; 65 % gas freed.

Temperature of the ullage: 60 °F = 520 °R.

Gasoline: RVP 13 (from API *MPMS* Ch. 19.4, Table 2, P_{VA} = 7.0 at 60 °F and M_V = 62 lb/lb-mole).

Volume loaded: 125,000 bbl.

5.1.2 Solution

The volume loaded is 125,000 bbl (42 gal/bbl) = 5,250,000 gal.

The average saturation factor for the compartments is (see Table 2):

$$K_S = 0.25(0.20) + 0.10(0.15) + 0.65(0.10) = 0.13$$

The loss from loading gasoline from Equation (2) is:

$$L_L \text{ lb/(1000 gal loaded)} = 12.46\ K_S\ P_{VA}\ M_V\ /T_V$$

$$L_L \text{ lb/(1000 gal loaded)} = (12.46)(0.13)(7.0)(62)/(520) = 1.35 \text{ lb/(1000 gal loaded)}$$

and the total loss is:

$$L_L = 1.35 \text{ lb}(5{,}250{,}000/1000) = 7100 \text{ lb}$$

5.2 Loss from Loading Crude Oil

5.2.1 Parameters

Marine vessel: ship.

Prior cargo: crude oil.

Compartment conditions prior to loading: 85 % uncleaned, 15 % cleaned.

Temperature of the ullage: 60 °F = 520 °R.

Crude oil: P_{VA} = 2.0 at 60 °F (from API *MPMS* Ch. 19.4, Table 2, M_V = 50 lb/lb-mole).

Volume loaded: 180,000 bbl.

5.2.2 Solution

The volume loaded is 180,000 bbl (42 gal/bbl) = 7,560,000 gal.

The average saturation factor for the compartments is (see Table 2; the previous cargo was crude oil, which is considered volatile per the definition given in 3.2):

$$K_S = 0.85(0.20) + 0.15(0.10) = 0.185$$

The loss from loading crude oil from Equation (2) is:

$$L_L \text{ lb/(1000 gal loaded)} = 12.46\ K_S\ P_{VA}\ M_V\ /T_V$$

$$L_L \text{ lb/(1000 gal loaded)} = 12.46\ (0.185)(2.0)(50)/(520) = 0.443 \text{ lb/(1000 gal loaded)}$$

and the total loss is:

$$L_L = (0.443 \text{ lb})(7{,}560{,}000/1000) = 3350 \text{ lb}$$

5.3 Loss from Loading Ballast Water

5.3.1 Parameters

Marine vessel: ocean barge.

Prior cargo: crude oil.

Compartment conditions prior to loading ballast water: 80 % had been loaded to 1 ft ullage, 20 % had been lightered to 10 ft ullage.

Temperature of the ullage: 70 °F = 530 °R.

Crude oil: P_{VA} = 3.8 at 60 °F (from API *MPMS* Ch. 19.4, Table 2, M_V = 50 lb/lb-mole).

Volume unloaded: 600,000 bbl of crude oil; 17 % of the volume is filled with ballast water after unloading the crude oil.

5.3.2 Solution

The volume of ballast water loaded is 0.17(600,000 bbl)(42 gal/bbl) = 4,284,000 gal.

The average saturation factor for the compartments is (see Table 3):

$$K_S = 0.80(0.20) + 0.20(0.35) = 0.23$$

The loss from loading ballast water from Equation (2) is:

$$L_L \text{ lb/(1000 gal loaded)} = 12.46\ K_S\ P_{VA}\ M_V / T_V$$

$$L_L \text{ lb/(1000 gal loaded)} = 12.46(0.23)(3.8)(50)/(530) = 1.03 \text{ lb/(1000 gal loaded)}$$

and the total loss is:

$$L_L = 1.03 \text{ lb } (4{,}284{,}000/1000) = 4400 \text{ lb}$$

6 Development of the Equations for Estimating Loss

No new data has been used to develop the emission estimates presented in this edition of this document. The emissions estimates in this edition are based on the same data as the previous edition [3], but the emission estimate formulas of this edition are expressed differently than the previous edition so that the formulas are more transparent. The formulas are based the ideal gas law as shown in 6.1 and summarized in Equation (1) shown as follows.

The values shown in Table 2 for the saturation factor K_S are based on solving Equation (2) for K_S from the values given for the loading loss L_L in the previous edition [3] (i.e. the new saturation factors were simply back-calculated from the old emission factors).

6.1 General Expression for Loading Loss

Loading loss can be determined using the general expression:

$$\text{(loading loss)} = \text{(volume loaded)(a saturation factor)(ideal vapor density at equilibrium)}$$

The ideal vapor density at equilibrium may be derived as follows:

density = (mass)/(volume)

mass = (number of moles, n)(molecular weight of the vapors, M_V)

The density of the vapors W_V for a volume V_L is therefore:

$W_V = (nM_V)/V_L$, and at equilibrium, the ideal gas law states:

$n/V_L = P_{VA} /(RT_V)$

Combining these equations:

$W_V = (P_{VA} M_V)/(RT_V)$

where

W_V is the density of the stock vapors;

P_{VA} is the true vapor pressure of the stock liquid being loaded;

M_V is the molecular weight of the stock vapors;

R is the ideal gas constant;

T_V is the absolute temperature of the ullage.

The mass of vapors at ideal equilibrium conditions in a volume V_L may therefore be expressed as:

(mass of vapors) = (volume)(density)

(mass of vapors) = $V_L (P_{VA} M_V)/(RT_V)$

The vapors of petroleum stocks are typically heavier than air, however. Gravity causes these vapors to settle toward the bottom of a given space. This gravity action results in the vapor density at the higher portions of the vapor space being less than that predicted for equilibrium conditions by the ideal gas law. The extent to which the vapor concentration is less than the ideal equilibrium concentration may be expressed as a saturation factor K_S.

The quantity of vapors L_L that are lost (displaced) from a given space during loading operations may therefore be expressed as follows:

$$L_L = V_L K_S P_{VA} M_V /(RT_V) \quad (1)$$

Substituting 10.731 (psia ft^3)/(lb-mole °R) for the ideal gas constant R and 1000 gal for the volume V_L, and including a conversion factor of 7.48 gal/ft^3, this equation becomes:

$$L_L \text{ lb/(1000 gal loaded)} = 12.46 K_S P_{VA} M_V /T_V \quad (2)$$

The loading loss consists of two components: loss of vapors resident in the vapor space from the prior cargo, and loss of vapors generated during loading of the new cargo. If the prior cargo and the new cargo are different, a more precise loss estimate might be determined by using their respective vapor pressures and vapor molecular weights for separate resident and generated loss estimates.

6.2 Saturation Factors for Loading Gasoline

The gasoline loading saturation factors of Table 2 were developed from Table A.1, which is based on data for which P_{VA} was 8 psia (see F.1.1) and a typical vapor molecular weight M_V of 64 lb/lb-mole was assumed (see B.3). Assuming a temperature T_V of 523 °R (63 °F) (a reasonable annual average temperature in the continental United States, and consistent with what had been used in API *MPMS* Ch. 19.1 [10] for filling fixed roof tanks) and substituting these values into Equation (2):

$$L_L \text{ lb/(1000 gal loaded)} = 12.46\, K_S \text{ (8 psia)(64 lb/lb-mole)/(523 °R)}$$

$$L_L \text{ lb/(1000 gal loaded)} = 12.2\, K_S$$

Table A.1 provides the gasoline loading loss L_L for various vessels, prior cargos, and compartment treatments during the ballast voyage. These were used to determine the saturation factor K_S given in Table 2 for these various conditions. For example, for a barge whose prior cargo was volatile and whose compartment was uncleaned prior to loading, the saturation factor K_S for gasoline loading is calculated as:

$$3.9 = 12.2\, K_S, \text{ so } K_S = 3.9/12.2 = 0.32, \text{ which is rounded to 0.3 in Table 2}$$

The emission factors from Table A.1 and the corresponding saturation factors, where $K_S = L_L/12.2$, are summarized as follows. The Table 2 saturation factors were rounded to the nearest 0.05. The Table 2 saturation factors for loading other petroleum liquids were taken from AP-42 [8], Table 5.2-1.

Table 4—Saturation Factors for Gasoline Loading

Category	Vessel	Prior Cargo	Compartment Treatment During Ballast Voyage	Average Emission Factor (lb/1000 gal loaded) L_L	Saturation Factor $K_S = L_L/12.2$
1	Tanker/ocean barge	Volatile	Uncleaned	2.6	0.21
2	Tanker/ocean barge	Volatile	Ballasted	1.7	0.14
3	Tanker/ocean barge	Volatile	Cleaned	1.5	0.12
4	Tanker/ocean barge	Volatile	Gas freed	0.7	0.06
		Nonvolatile	Ballasted, cleaned, gas freed, uncleaned		
5	Barge	Volatile	Uncleaned	3.9	0.32
6	Barge	Volatile	Cleaned, gas freed	2.0	0.16
		Nonvolatile	Uncleaned, cleaned, gas freed		

API 2524 [2] reports data from 19 tests of gasoline loading into uncleaned barge compartments, with true vapor pressure reported for three of these tests. A comparison of the measured emissions to the emissions predicted is given as follows.

Table 5 shows that the API *MPMS* Ch. 19.5 loss estimates are closer than the API 2514A-1981 [3] loss estimates to the measured loss reported in API 2524.

Additional data are available from tests reported by Spectrasyne [4] and CONCAWE [5]. The objective of these tests was to use DIAL infrared technology to measure emissions from storage tanks, but these studies first measured emissions from barge loading in order to establish a correlation with DIAL measurements of the emissions plume. (DIAL is an acronym for differential absorption LIDAR, and LIDAR is an acronym for light detection and ranging—a light-based range finding system similar to RADAR, using a laser as the light source.)

Table 5—API 2524 Loss Data Compared to Predicted Loss

Test	Volume Loaded (bbl)	Volume Loaded (ft^3)	P_{VA} (psia)	Measured Loss ($lb/10^3$ gal)	*MPMS* Chapter 19.5 Loss [a] ($lb/10^3$ gal)	API 2514A-1981 Loss ($lb/10^3$ gal)
121	2392	13,431	7.1	2.29	3.2	3.9
122	2404	13,498	7.1	2.18	3.2	3.9
123	2437	13,684	7.1	2.09	3.2	3.9

[a] Equation (2) with K_S = 0.3.

Barge loading was used to establish a correlation with DIAL measurements because the venting of barge loading emissions through a single stack allowed them to be directly measured for comparison with the downwind DIAL readings. The results of the vent measurements are summarized in Table 6 and compared to estimated values. The molecular weight of the stock vapor, M_V, was reported as 69 lb/lb-mole, but the true vapor pressure was not given. The emission estimates using Equation (2) are calculated at true vapor pressures of both 7 psia and 8 psia, in order to illustrate a range of likely results. In each case, the value for the saturation factor used in Equation (2) is 0.3.

Again, while the API 2514A-1981 loss factor gives a reasonable prediction of emissions, some improvement may be achieved by using Equation (2) with a saturation factor of 0.3 from this standard (API *MPMS* Ch. 19.5).

Table 6—CONCAWE Loss Data Compared to Predicted Loss

Test Set	Measured Emissions (kg)	Volume Loaded (m^3)	Measured Rate (kg/m^3)	Measured Rate (lb/Mgal)	API *MPMS* Ch. 19.5 [a] $P = 7$ psia (lb/Mgal)	API *MPMS* Ch. 19.5 [a] $P = 8$ psia (lb/Mgal)	API 2514A-1981 Loss (lb/Mgal)
Reference [4]	390	950	0.411	3.4	3.4	3.9	3.9
Reference [5]	435	950	0.458	3.8	3.4	3.9	3.9
average	412	950	0.434	3.6	3.4	3.9	3.9

[a] Equation (2) with K_S = 0.3.

6.3 Saturation Factors for Loading Crude Oil

The crude oil loading emission factors of Table 2 were developed from Table A.2, which is based on data for which P_{VA} was 4 psia (see A.3.2) and M_V was 58 lb/lb-mole and the vapor temperature T_V was 530 °R (see Table A.3). Substituting these values into Equation (2):

$$L_L \text{ lb/(1000 gal loaded)} = 12.46\ K_S \text{ (4 psia)(58 lb/lb-mole)/(530 °R)}$$

$$L_L \text{ lb/(1000 gal loaded)} = 5.5\ K_S$$

Table A.2 provides the crude oil loading loss L_L for various vessels, prior cargos, and compartment treatments during the ballast voyage. These were used to determine the saturation factor K_S given in Table 2 for these various conditions. For example, for a ship or ocean barge whose prior cargo was volatile and compartment was uncleaned prior to loading, the saturation factor K_S for crude oil loading is:

$$1.1 = 5.5\ K_S, \text{ so } K_S = 1.1/5.5 = 0.2$$

The emission factors from Table A.2 and the corresponding saturation factors, where $K_S = L_L/5.5$, are summarized as follows. The Table 2 saturation factors were rounded to the nearest 0.05.

Table 7—Saturation Factors for Crude Oil Loading

Category	Vessel	Prior Cargo	Compartment Treatment During Ballast Voyage	Average Emission Factor (lb/1000 gal loaded) L_L	Saturation Factor $K_S = L_L/5.5$
1	Tanker/ocean barge	Volatile	Uncleaned	1.1	0.20
2	Tanker/ocean barge	Volatile	Ballasted	0.7	0.13
3	Tanker/ocean barge	Volatile	Cleaned	0.6	0.11
4	Tanker/ocean barge	Volatile	Gas freed		
		Nonvolatile	Ballasted, cleaned, gas freed, uncleaned		

6.4 Saturation Factors for Loading Ballast Water

The ballast water loading emission factors of Table 3 were developed from Table A.4, which is based on data for which P_{VA} was 4 psia (see Annex E). Using the same value for M_V of 58 lb/lb-mole and the vapor temperature T_V was 530 °R as were used as for loading crude oil and substituting these values into Equation (2):

$$L_L \text{ lb/(1000 gal loaded)} = 12.46\ K_S \text{ (4 psia)(58 lb/lb-mole)/(530 °R)}$$

$$L_L \text{ lb/(1000 gal loaded)} = 5.5\ K_S$$

Table A.4 provides the crude oil ballasting loss L_L for various vessels, prior cargos, and compartment treatments during the ballast voyage. These were used to determine the saturation factor K_S given in Table 3 for these various conditions. For example, for a ship or ocean barge whose prior cargo was crude oil and compartment was fully loaded prior to dockside crude oil unloading, the saturation factor K_S for ballast water loading is:

$$1.2 = 5.5\ K_S, \text{ so } K_S = 1.2/5.5 = 0.22$$

The emission factors from Table A.4 and the corresponding saturation factors, where $K_S = L_L/5.5$, are summarized as follows. The Table 3 saturation factors were rounded to the nearest 0.05.

The volume of ballast water loaded as 17 % of the volume of crude oil unloaded for a typical facility is based on API 2514A-1981, which states that this percentage is based on a survey of 31 U.S. refineries.

Table 8—Saturation Factors for Loading Ballast Water

Category	Compartment Condition Prior to Dockside Cargo Discharge	Average Emission Factor (lb/1000 gal water loaded) L_L	Saturation Factor $K_S = L_L/5.5$
1	Fully loaded	1.2	0.22
2	Lightered or previously short loaded	1.9	0.35

The higher emission estimate for lightered or previously short-loaded vessels represents a scenario in which the vessel arrives with a larger ullage than is typical of a fully-loaded vessel and thus it arrives with a larger volume of vapors.

Annex A

Historical Development of the Emission Factors

A.1 Introduction

The First Edition of API Bulletin 2514, *Evaporation Loss from Tank Cars, Tank Trucks, and Marine Vessels*, was published in 1959 [6]. In 1976, the First Edition of API Bulletin 2514A, *Atmospheric Hydrocarbon Emissions from Marine Vessel Transfer Operations*, was published, utilizing the API Bulletin 2514 content concerning marine vessels only. Subsequently, industry-wide measurement programs were conducted to prepare the Second Edition of API Publication 2514A. These programs provided emission data for other marine operations.

All available emissions data on marine operations then practiced in the United States, excluding the operation of crude oil washing, were compiled for API Publication 2514A-1981 [3]. These data were developed after 1974 and resulted from test programs that used comparable vapor emission measurement procedures. These procedures represented a significant improvement over those used to develop the very limited data upon which the 1959 Edition of API Bulletin 2514 was based.

A.2 Emissions from Loading Operations

A.2.1 Gasoline Loading

A.2.1.1 Data Base

The emission factors for gasoline loading are based on tests of 122 compartments taken during nearly 100 ship and barge loading operations. Emissions were determined by periodically sampling vapors displaced from individual compartments during a complete loading cycle. The testing procedure is summarized in Annex B. The data are summarized in Annex C. The gasoline cargoes spanned a volatility range of 3.4 psia to 12.7 psia true vapor pressure. The test data were collected during all seasons of the year and in many regions of the country, chiefly during routine loading operations.

A.2.1.2 Development of Emission Factors

Analysis of the gasoline loading test data showed the need for six categories of emission factors to account for differences in the type of vessel, prior cargo, and arrival condition.

The first broad distinction was the separation of shallow draft barges and larger vessels. Ships normally had lower emission factors than shallow draft barges. Ocean-going barges had emission factors typical of ships.

The emission data were further differentiated by the volatility of the prior cargo. Volatile prior cargoes, defined as cargoes having a true vapor pressure greater than 1.5 psia, resulted in higher arrival vapor concentrations and higher total emissions than nonvolatile prior cargoes, all other aspects being equal.

Finally, the data were grouped according to the operations conducted on each compartment after discharge of the prior cargo. Ballasting, cleaning, and gas-freeing operations each affected the emissions observed during the subsequent loading differently. Compartments in which cleaning was limited to washing out the heel of prior cargo with water were classified as uncleaned for purposes of grouping the data.

Analysis of the test data in each of the six categories resulted in the development of the emission factors presented in Table A.1. Their development is described in Annex C.

Table A.1—Total Emission Factors for Gasoline Loading

				Average Emission Factors (lb/1000 gal loaded)	
Category	**Vessel**	**Prior Cargo**	**Compartment Treatment During Ballast Voyage**	**By Category**	**Typical Overall**
1	Tanker/ocean barge	Volatile	Uncleaned	2.6	1.8
2	Tanker/ocean barge	Volatile	Ballasted	1.7	
3	Tanker/ocean barge	Volatile	Cleaned	1.5	
4	Tanker/ocean barge	Volatile	Gas freed	0.7	
		Nonvolatile	Ballasted, cleaned, gas freed, uncleaned		
5	Barge	Volatile	Uncleaned	3.9	3.4
6	Barge	Volatile	Cleaned, gas freed	2.0	
		Nonvolatile	Uncleaned, cleaned, gas freed		

A.2.1.3 Emission Correlation

For API 2514A-1981, a mathematical analysis was performed to relate the generated loading emissions to the true vapor pressure of the gasoline loaded. The resulting correlation was not found to be statistically significant and did not improve upon the emission predictions obtained using the average emission factors in Table A.1. Various unmeasured random and systematic effects obscured the effect of cargo vapor pressure on the generated emissions. Consequently, no correlation was recommended then for predicting gasoline loading emissions as function of the vapor pressure of the gasoline loaded.

In this standard (API *MPMS* Ch. 19.5), however, vapor pressure is included in the variables that estimate emission loss based on the theory presented in Section 6. This is validated by the improved fit to the API 2524 data that including the vapor pressure provides.

A.2.1.4 Assessment of Predictions

The emission factors presented in Table A.1 are based on a broad data base and describe emissions from typical gasoline loading operations. However, every loading operation appears unique in some respect. Differences related to the design and operation of individual vessels and marine terminals, as well as the characteristics and environment of the loaded prior cargoes, create significant variability in the observed emissions within each of the six categories.

A statistical analysis of the variability as it relates to the confidence in the predictions is summarized in Annex C. The analysis provides a measure of the uncertainty in the estimated emissions when the emission factors are applied. The range of emission factors for each of the six categories at 90 % confidence for both 1 and 100 compartment loadings are presented in Annex C (see Table C.2). As shown there, the range narrows greatly as the number of compartments being estimated increases.

A.2.2 Crude Oil Loading

A.2.2.1 Data Base

Emission tests of 67 compartments during 16 vessel loading operations were available for development of the crude oil loading emission factors and correlation. Emissions were monitored by sampling vapors vented from individual compartments during a complete loading cycle. The testing procedure is summarized in Annex B. All tests were conducted during routine ship loading operations.

The emission data are summarized in Annex D and span the following ranges:

	Range
RVP of crude loaded (lb)	0.2 to 7.0
Loaded cargo temperature (°F)	68 to 120
P_{VA} of crude loaded (psia)	1.0 to 6.5

Six different crude oils were loaded during the 16 tests. The majority were Southern California crudes, which tend to be moderately volatile, medium-gravity oils. The crude oils loaded were: Santa Barbara Offshore (3 tests); Montalvo (3 tests); Ventura (3 tests); Ventura plus 10 % natural gasoline (4 tests); San Joaquin Heavy (2 tests); and Nigerian Light (1 test).

A.2.2.2 Development of Emission Factors

Table A.2 presents the emission factors in lb/1000 gal of crude oil loaded. These factors were developed for several categories, depending on compartment treatment during the ballast voyage and the volatility of the prior cargo. The factors apply to ships, excluding VLCCs, and to ocean-going barges.

Table A.2—Total Emission Factors for Crude Oil Loading

				Average Emission Factors (lb/1000 gal loaded)	
Category	**Vessel**	**Prior Cargo**	**Compartment Treatment During Ballast Voyage**	**By Category**	**Typical Overall**
1	Tanker/ocean barge	Volatile	Uncleaned	1.1	1.0
2	Tanker/ocean barge	Volatile	Ballasted	0.7	
3	Tanker/ocean barge	Volatile	Cleaned	0.6	
4	Tanker/ocean barge	Volatile	Gas freed		
		Nonvolatile	Ballasted, cleaned, gas freed, uncleaned		

The emission factors for Categories 1, 3, and 4 were obtained by arithmetically averaging the emission data in each of these three categories. Direct comparison of the average emission factors for the three categories was difficult since the crude oil loading emission factors were found to depend on the true vapor pressure of the crude oil loaded, but the average true vapor pressure of the crudes was not the same for the three categories. In order to compare the emission factors and provide the best estimate of emissions, the average emission factors in Table 2 were adjusted to a common basis of 4 psia true vapor pressure using Equation (A.1) and Equation (A.2):

$$E_T = E_A + E_G \tag{A.1}$$

where

E_T is the total crude oil loading emission factor (lb/1000 gal loaded);

E_A is the arrival emission factor, associated with the hydrocarbon vapor in the compartment prior to loading (lb/1000 gal loaded);

E_G is the generated emission factor, associated with the hydrocarbon vapor generated by evaporation during loading (lb/1000 gal loaded).

Average values of E_A for each compartment category are given in Table A.3. E_G can be calculated from the following equation:

$$E_G = 1.84\,[0.44(P_{VA}) - 0.42]M_V\,G/T_V \quad \text{(A.2)}$$

where

P_{VA} is the true vapor pressure of loaded crude oil (psia);

M_V is the average vapor molecular weight (lb/lb-mole);

G is the vapor growth factor (dimensionless);

T_V is the absolute temperature of the ullage (°R).

Table A.3—Average Values of Variables for Crude Oil Loading Emission Equation

Category	**Arrival Emission Factors,** E_A (lb/1000 gal loaded)	**Vapor Molecular Weight,** M_V (lb/lb-mole)	**Vapor Growth Factor** (dimensionless)	**Average Vapor Temperature** (°R)
1	0.86	58	1.02	530
2	0.46	58	1.02	530
3 and 4	0.33	58	1.02	530

The data base for Table A.2, Category 2 was too sparse to provide a representative average emission factor. Instead, the emission factor was estimated by adjusting the crude oil emission factor for Category 1 by the ratio of gasoline loading emission factors between Category 2 and Category 1.

Further details on development of the average emission factors are given in Annex D.

A.2.2.3 Development of Emission Correlation

Several equations for correlating the emission factors with characteristics of the cargo loaded and prior cargo were examined. A statistically significant correlation was developed that relates the generated emission factor to the true vapor pressure of the cargo loaded. The relationship is given by Equation (A.2). Its development is described in Annex D.

No statistically significant correlations were found to relate the arrival portion of the emission factor with characteristics of the prior cargo. The most promising correlating variable—the vapor pressure of the prior cargo—was not available for most tests. Other potential correlating parameters that were available, such as prior cargo ullage, did not correlate significantly with the arrival emission factors.

Use of Equation (A.1) and Equation (A.2) whenever the true vapor pressure of the loaded cargo is known will improve the estimate of crude oil loading emissions as compared with the use of the average emission factors given in Table A.2.

A.2.2.4 Assessment of Predictions

For most of the 16 crude oil loading operations, the test data were averaged for all the compartments tested on each vessel and an average emission factor was calculated for the vessel rather than for the individual compartments. Thus, the data base, though sizable, could not be used to develop a statistical analysis of the crude oil loading emission factors. However, the average emission factors in Table A.2, as well as the correlation given by Equation (A.2), are considered to be representative because of the large number of compartment loadings incorporated in the data base.

The correlation was based on emission data from moderate-volatility crude oils with a range of 1.0 psia to 6.5 psia true vapor pressure. Some loss in accuracy can be expected if the correlation is applied outside this range.

Emission estimates of an isolated loading are necessarily subject to greater uncertainties than emission estimates of a large number of loadings because unique operating conditions associated with a particular loading operation. With a large number of vessel loadings, random and systematic effects introduced by differing operating practices of various tankers and operators serving a terminal will tend to average out and reduce the uncertainty in the overall emission estimates.

A.3 Emissions from Ballasting Operations

A.3.1 Data Base

The data base for crude oil ballasting emissions was developed during a test program conducted at 31 refineries in the United States during a 10-month period. Because little or no gasoline is unloaded at these refineries, no test data or emission factors for ballasting gasoline tankers were developed.

Crude oil ballasting emissions were determined by measuring the concentration and composition of vapors displaced from individual compartments during normal dockside ballasting operations. The testing procedure is summarized in Annex B.

The data base is summarized in Annex E and includes tests during 21 ballasting operations involving 14 major crude oils that are routinely brought into U.S. refineries. Emissions were measured from 54 separate compartments. Each test included the measurement of emissions from one to six ballasted compartments. The range of the data base is as follows.

	Range
RVP of crude discharged (psi)	0.7 to 8.6
Crude oil temperature during discharge (°F)	42.0 to 132.0
P_{VA} of crude discharged (psia)	1.3 to 8.4
Gravity of crude discharged (°API)	24.7 to 41.0
Arrival ullage (ft)	0.9 to 44.5
Compartment depth (ft)	47.0 to 77.0

A.3.2 Development of Average Emission Factors

Table A.4 presents average total hydrocarbon emission factors, in lb/1000 gal of ballast water loaded, for ballasting into uncleaned crude oil cargo compartments. The factors were developed for two categories, depending on the degree to which a compartment is filled just prior to discharge. The first category applies to compartments with crude oil true ullage (distance from deck to cargo surface) equal to or less than 5 ft just prior to discharge at the dock. The second applies to lightered or previously short-loaded compartments, with a true ullage greater than 5 ft just prior to dockside discharge.

Table A.4—Total Emission Factors for Crude Oil Ballasting

		Average Emission Factors (lb/1000 gal ballast water loaded)	
Category	**Compartment Condition Prior to Dockside Cargo Discharge**	**By Category**	**Typical Overall**
1	Fully loaded	1.2	1.4
2	Lightered or previously short loaded	1.9	1.4

Further details on the development of the average emission factors are given in Annex E.

A.3.3 Development of Emission Correlations

As with the crude oil loading emission factors, the ballasting emission factors were found to depend on the true vapor pressure of the discharged crude oil. The emission factors were also found to depend on the true ullage of the cargo prior to discharge. An empirical equation, Equation (A.3), was developed to relate the ballasting emissions to these parameters. The use of Equation (A.3) improves on the emission estimates obtained using the average emission factors in Table A.4.

$$E_B = 0.31 + 0.20\ (P_{VA}) + 0.01\ (P_{VA})\ (U_A) \qquad \text{(A.3)}$$

where

E_B is the ballasting emission factor (lb/1000 gal ballast water loaded);

P_{VA} is the true vapor pressure of discharged crude oil (psia);

U_A is the arrival cargo true ullage, prior to dockside discharge, measured from the deck (ft).

The equation was derived by combining variables that logically represent the two ballasting emission components, arrival and generated vapor. One term in the equation that includes only true vapor pressure can be thought of as representing emissions generated during unloading. Another term that includes both true vapor pressure and ullage represents the vapors present upon arrival. However, because the arrival and generated vapors are often intermixed during discharge, it was not possible to correlate each emission component separately. Instead, the arrival and generated vapors were handled together in the mathematical regression analysis that was used to develop the equation. Development of the correlation is described in Annex E.

A.3.4 Assessment of Predictions

The data base used to develop Equation (A.3) encompasses crude oils in the volatility range of 1.3 psia to 8.4 psia true vapor pressure. Some loss in accuracy can be expected if the correlation is applied outside this range.

The ballasting emission factors and correlation can be used with the most confidence when applied to estimate emissions from a wide range of operations at a marine terminal. Random and systematic impacts on emissions due to varying operating practices and designs of ships and marine terminals will tend to average out for larger numbers of ballasting operations. Emission estimates for fewer ballastings are subject to somewhat larger uncertainties. A statistical analysis of the variability in estimated emissions as it relates to the confidence in the predicted values is presented in Annex E. The analysis provides a measure of uncertainty in the estimated emissions when the emission factors and correlation are applied.

Annex B

Measurement Procedures and Data Analysis Techniques

B.1 Scope of Test Programs

The test programs from which the marine emissions data base was developed were designed to determine the total hydrocarbon emissions from a vessel's cargo tanks during gasoline and crude oil loading and during cargo tank ballasting after the discharge of crude oil. In general, the measurement procedures and data analysis techniques used in these programs followed those developed as part of the Western Oil and Gas Association (WOGA) Marine Measurement Program [11]. The tests were conducted during all seasons of the year and in many regions of the country, usually during routine operations. U.S. Coast Guard approval of the test procedure was obtained to ensure all safety requirements were satisfied.

The following parameters were recorded, when appropriate, for each compartment tested.

1) General Information:

   a) date and vessel name;

   b) identification number, capacity, and depth of compartment;

   c) ambient, emitted vapor, and cargo/ballast water temperatures.

2) For loading tests:

   a) compartment condition upon arrival (ballast voyage treatment and prior cargo);

   b) loading rate;

   c) identification, volume, and Reid vapor pressure of loaded cargo (plus specific gravity and viscosity of crude oil).

3) For ballasting tests:

   a) true ullage prior to dockside discharge of cargo;

   b) unloading and ballasting rates; time between unloading and start of ballasting operation;

   c) identification, Reid vapor pressure, specific gravity, and viscosity of discharged crude oil; volume of ballast water loaded.

B.2 Measurement Procedures

The concentration of the hydrocarbon vapors emitted from each tested compartment was measured periodically during a complete loading/ballasting cycle. In general, the measurements were made with an MSA Model 53 gascope or a similar instrument. The gascope was connected to a probe that was inserted into the ullage trunk to approximately deck level. Before and after each concentration reading, the gascope was zeroed with air supplied through a line extending over the upwind side of the ship. The true ullage at the time of each concentration reading was determined by a continuous metering tape or by manual gaging.

Each gascope was connected in series with a vapor sample bag that enabled concentrations readings and samples to be taken simultaneously. The vapor samples were subsequently analyzed by gas chromatography or nondispersive infrared techniques using laboratory equipment. The sample analyses were used to calibrate the respective gascope.

In some of the gasoline loading tests, gascopes were not used. In these tests, vapor samples analyses were used exclusively to determine the hydrocarbon concentration of the vented vapors.

B.3 Data Analysis

To calculate an emission factor for each test, it was necessary to determine the average hydrocarbon concentration, its molecular weight, and the total volume of the vented vapor. These values were obtained as described as follows.

The corrected vapor concentration readings (the gascope readings with the calibration factor applied) were plotted versus true ullage to determine the average hydrocarbon concentration for each test. A typical emission profile is shown in Figure B.1. These curves were then graphically or analytically integrated to determine an average vented hydrocarbon concentration.

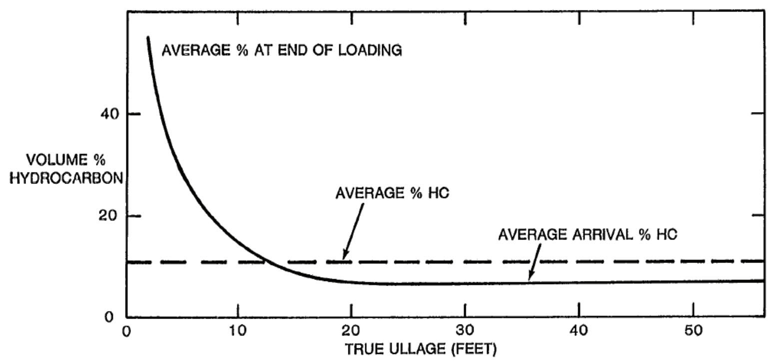

Figure B.1—Typical Loading Emissions Profile

Molecular weight data, usually obtained by chromatographic analyses of the vapor samples, were plotted in a similar fashion and used to determine an average molecular weight for each test. For some of the gasoline loading tests, molecular weight was not determined by vapor analysis. In these cases, a typical vapor weight of 64 was assumed.

For loading operations, the volume of the vented vapor was calculated from the loaded cargo volume and an equation to account for the increase in vapor volume due to the generation of hydrocarbon vapor during loading. This equation was derived from mass balance calculations, using the average hydrocarbon concentrations, before, during, and at the end of loading. The vented vapor volume is given by the following equation:

$$V_V = \left[\frac{(1 - X_T)\left(\frac{U_I}{U_I - U_f}\right) - (1 - X_R)\left(\frac{U_f}{U_I - U_f}\right)}{(1 - X_V)} \right] V_L \qquad \text{(B.1)}$$

where

V_V is the total vented vapor volume (ft^3 at standard conditions);

V_L is the volume of liquid loaded (ft^3 at 60 °F);

X_T is the volumetric average hydrocarbon concentration of arrival vapor;

X_V is the volumetric average hydrocarbon concentration of vented vapor;

X_R is the volumetric average hydrocarbon concentration of remaining vapor;

U_I is the total tank depth (ft);

U_f is the final ullage (ft).

The vapor growth factor was calculated from the vented vapor volume using Equation (B.2):

$$G = \frac{V_V - V_L}{V_L} + 1 \tag{B.2}$$

The resultant vapor growth factors were then used to calculate the average emission factors for each loading test.

For ballasting operations, it was assumed that the volume of vapor vented was equal to the volume of ballast water loaded (G = 1).

The complete test procedure from the WOGA marine measurement program and the derivation of the equation for vented vapor volume are included in the API Documentation File for Annex B.

Annex C

Development of Average Emission Factors and Confidence Intervals for Gasoline Loading

C.1 Data Base

The data base for gasoline loading emissions consists of emission measurements from 122 individual vessel compartments. These data were separated into six categories, as a function of vessel type, prior cargo, and ballast voyage compartment treatment. The emission data from each compartment were separately analyzed to determine arrival, generated, and total emission factors. These emission factors and the categories are discussed in A.2.1.2.

The data base is summarized in Table C.1. This table includes the number of compartments in each category, and the arithmetic means, standard deviations, and minimum and maximum values of the arrival (E_A), generated (E_G), and total (E_T) emission factors.

Table C.1—Average Measured Emission Factors for Gasoline Loading

Category	Compartments	Arithmetic Mean (lb/1000 gal)	Standard Deviation	Minimum Value	Maximum Value
Category 1	44				
E_A		1.99	1.149	0.32	6.10
E_G		0.59	0.614	0.00	3.26
E_T		2.58	1.197	0.53	6.47
Category 2	14				
E_A		0.71	0.644	0.00	2.22
E_G		0.96	0.972	0.06	3.78
E_T		1.67	1.064	0.44	4.49
Category 3	7				
E_A		0.55	0.404	0.07	1.30
E_G		0.89	0.443	0.44	1.72
E_T		1.44	0.491	0.69	2.00
Category 4	36				
E_A		0.13	0.173	0.00	0.60
E_G		0.56	0.355	0.12	1.80
E_T		0.69	0.430	0.14	2.08
Category 5	17				
E_A		2.27	0.862	0.34	3.64
E_G		1.57	0.756	0.55	2.83
E_T		3.85	0.943	2.31	5.58
Category 6	4				
E_A		0.00	0.000	0.00	0.00
E_G		2.02	0.369	1.48	2.30
E_T		2.02	0.369	1.48	2.30

C.2 Data Analysis of Average Emission Factors

The first step in the data analysis was to determine the distribution of the E_T values within each category. This analysis showed that the E_T values are not normally distributed. Instead, the distribution of E_T is skewed, such that a large number of values are below the arithmetic mean and a smaller number of values are distributed above the arithmetic mean.

In cases where a skewed distribution exists, it is standard practice to transform the data base (that is, the E_T values) into a set of values that is normally distributed. By taking the logarithm of each E_T value, a normal distribution was obtained. Standard statistical tests were performed that showed that it was acceptable to assume that the data in each category, as well as the combined data base, were log-normally distributed. Means and confidence intervals were calculated for the logarithms of the E_T values. These means and confidence intervals were then transformed back to the original units of measurement.

The statistical analysis outlined above provides the best estimate of the mean emission factors and allows for the calculation of confidence intervals for any number of compartment loading operations. For illustration purposes, 90 % confidence intervals were calculated for a single compartment loading, as well as for an average emission factor for 100 compartment loadings. Table C.2 presents these means and confidence intervals for each category.

Table C.2—Calculated Estimates of Mean Total Emission Factors and Confidence Intervals for Gasoline Loading

		90 % Confidence Intervals for Mean E_T (lb/1000 gal)	
Category	**Mean** E_T (lb/1000 gal)	**Single Compartment**	**Average of 100 Compartments**
1	2.63	1.07 to 6.43	2.24 to 3.09
2	1.70	0.54 to 5.35	1.24 to 2.34
3	1.47	0.64 to 3.35	1.09 to 1.99
4	0.69	0.26 to 1.85	0.58 to 0.84
5	3.86	2.44 to 6.10	3.43 to 4.33
6	2.03	1.20 to 3.45	1.60 to 2.59

The statistically-developed, best estimates of the means, given in Table C.2, are extremely close to the arithmetic means of the original data in Table C.1.

The confidence intervals in Table C.2 can be interpreted to mean that there is a 90 % confidence that emission factors for future loadings of a single compartment or the average of 100 compartments will be within the given intervals. These results clearly show that the calculated mean values provide better estimates of emissions for a large number of loading operations than for any individual single compartment loading.

All supporting data and a more detailed discussion of the statistical analysis are in the API Documentation File for Annex C.

Annex D

Development of Average Emission Factors and Correlation for Crude Oil Loading

D.1 Data Base

The data base for crude oil loading emissions consists of emission measurements from 16 separate vessel operations, each of which represents averages of from 1 to 11 different compartments. The entire data base represents the measured emissions from 67 vessel compartments. These data were separated into three categories, as a function of prior cargo and ballast voyage compartment treatment. The emission data from each separate operation were separately analyzed to determine arrival, generated, and total emission factors. These emission factors and categories are discussed in A.2.2.2.

The data base is summarized in Table D.1. This table includes the number of operations and compartments tested in each category and the arithmetic means, standard deviations, and minimum and maximum values of the arrival (E_A), generated (E_G), and total (E_T) emission factors. The statistics are also presented in the table for the true vapor pressures of the loaded crude oils, since the true vapor pressure data were used in the development of an emission estimating correlation.

D.2 Data Analysis of Average Emission Factors

No statistical analysis of the emission data from each category was performed due to the limited number of separate vessel operations tested in two of the three categories. No confidence intervals could be developed since emissions from several compartments had been combined into one set of calculated emission factors for each separate operation. However, because of the large number of compartment loadings represented by the data base, it was judged that the data base as a whole was extensive enough to support the development of representative average factors.

To develop the best estimates of the average emission factors (see Table A.2), two modifications were made to the arithmetic averages of the data shown in Table D.1. First, the differences in the average true vapor pressure for each category were accounted for by adjusting the average measured E_T values to a common true vapor pressure of 4.0 psia. This adjustment was made by using the correlation discussed in D.3 and given by Equation (A.1) and (A.2). Average values for the other variables in the correlation were used to develop the best estimates of E_T values that were consistent for each category. This procedure was used to determine E_T values for Categories 1 and 3/4.

For Category 2, the average emission factor in Table A.2 was developed from a comparison with the gasoline loading data from Table C.2. This approach was necessary since there were only two Category 2 crude oil tests conducted, the conditions during those tests were not representative, and the results were not consistent with the results in the other categories. Therefore, the crude oil data for Category 1 was modified using the ratio of gasoline loading emission factors for Categories 1 and 2 to obtain a crude oil emission factor for Category 2. This follows from the assumption that the ballasting of a crude oil compartment will reduce the subsequent crude oil emission factor as compared with an uncleaned, unballasted compartment to the same degree as was measured for the similar gasoline loading cases.

D.3 Development of Crude Oil Loading Emission Correlation

Based on an analysis of the effects of various cargo and operational parameters on crude oil loading emissions, it was determined that the generated emissions could be related to the true vapor pressure of the loaded crude oil. Any effects that other parameters may have on crude oil loading emissions could not be quantified within the accuracy of the data and the randomly variable nature of other parameters.

Table D.1—Average Measured Emission Factors for Crude Oil Loading

Category	Number of Vessel Operations/ Compartments	Arithmetic Mean	Standard Deviation	Minimum Value	Maximum Value
Category 1	3/13				
P_{VA} (psia)		2.30	1.836	1.0	4.4
E_A (lb/1000 gal)		0.86	0.243	0.60	1.08
E_G (lb/1000 gal)		0.11	0.196	0.00	0.34
E_T (lb/1000 gal)		0.98	0.337	0.60	1.25
Category 2	2/3				
P_{VA} (psia)		2.25	1.768	1.0	3.5
E_A (lb/1000 gal)		1.06	0.346	0.81	1.30
E_G (lb/1000 gal)		0.10	0.148	0.00	0.21
E_T (lb/1000 gal)		1.16	0.198	1.02	1.30
Category 3/4	11/51				
P_{VA} (psia)		4.31	1.910	1.2	6.5
E_A (lb/1000 gal)		0.33	0.215	0.05	0.75
E_G (lb/1000 gal)		0.33	0.262	0.00	0.84
E_T (lb/1000 gal)		0.65	0.257	0.20	0.98

From regression and residual analyses, the following equation was developed to relate the concentration (in volume percent) of the generated vapors (C_G) to the true vapor pressure (in psia) of the loaded crude oil:

$$C_G = -0.42 + 0.44\,(P_{VA}) \tag{D.1}$$

The correlation for this relationship is statistically significant, indicating there is an effect of true vapor pressure on C_G.

To use the relationship given by Equation (D.1) to predict total emissions, the following equation was theoretically developed from the ideal gas law to relate the generated emission factor (E_G) to the concentration of generated vapors (C_G).

$$E_G = \frac{1.84(C_G)(M_V)(G)}{T_V} \tag{D.2}$$

where

E_G is the generated emission factor (lb/1000 gal loaded);

C_G is the average concentration of generated vapors (vol %);

M_V is the molecular weight of generated vapors (lb/lb-mole);

G is the vapor growth factor (dimensionless);

T_V is the vapor temperature (°R = 460 + °F).

For this analysis, the average concentration of generated vapors was determined by the difference between the average total concentration and the average concentration of the arrival vapor.

The generated emission factor (E_G) is related to the total emission factor (E_T) by the following equation:

$$E_T = E_A + E_G \quad \text{(D.3)}$$

where

E_T is the total loading emission factor (lb/1000 gal);

E_A is the average arrival emission factor (lb/1000 gal);

E_G is the generated emission factor (lb/1000 gal).

By combining Equation (D.1), Equation (D.2), and Equation (D.3), an equation relating total crude oil loading emissions to true vapor pressure of the loaded crude oil is obtained.

All supporting data, equation derivations, and the procedures used to calculate the average emissions factors and the correlation are in the API Documentation File for Annex D.

Annex E

Development of Average Emission Factors, Confidence Intervals, and Correlation for Crude Oil Ballasting

E.1 Data Base

The data base for crude oil ballasting emissions consists of emission measurements from 54 individual vessel compartments. These data were separated into two categories, as a function of the true cargo ullage in the compartment prior to dockside discharge. The emission data from each compartment were analyzed separately to determine total emission factors. These emission factors and the categories are discussed in A.3.2.

The data base is summarized in Table E.1. This table includes the arithmetic means, standard deviations, and minimum and maximum values of the total ballasting emission factors (E_B). The statistics are also presented in the table for the true vapor pressure of the discharged crude oil and the true cargo ullage prior to dockside discharge (U_A), since the true vapor pressure and U_A data were used in the development of an emission estimating correlation.

E.2 Data Analysis of Average Emission Factors

A statistical analysis of the emission data from each category was performed. As with the gasoline loading data described in Annex C, the crude oil ballasting data were found to be log-normally distributed. Therefore, the statistical procedures described in C.2 were used to develop means and confidence intervals for future ballasting operations in each category. These results are presented in Table E.2.

To develop the best estimates of the average emission factors (given in Table A.4), the average emission factors were adjusted to the same true vapor pressure, using the correlation discussed in E.3 and given by Equation (A.3). Since the average true vapor pressure of the entire data base was approximately 4 psia, the emission factors were calculated for a true vapor pressure of 4 psia and for typical U_A values measured in each category. This procedure is similar to that used to develop the average crude oil loading emission factors, as discussed in Annex D.

E.3 Development of the Crude Oil Ballasting Emission Correlation

Based on an analysis of the effects of various cargo and operational parameters on crude oil ballasting emissions, it was determined that ballasting emissions could be related to the true vapor pressure of the discharged crude oil and the true ullage (U_A) of the cargo prior to dockside discharge. Any effects that other parameters may have on crude oil ballasting emissions could not be quantified within the accuracy of the data and the randomly variable nature of other parameters.

From regression and residual analyses, the following equation was developed to relate the total ballasting emission factor (E_B) to the true vapor pressure and the true ullage prior to dockside discharge (U_A):

$$E_B = 0.31 + 0.20\,(P_{VA}) + 0.01\,(P_{VA})\,(U_A) \qquad \text{(E.1)}$$

where

E_B is the total ballasting emission factor (lb/1000 gal);

P_{VA} is the true vapor pressure of discharged crude oil (psia);

U_A is the true ullage prior to dockside discharge (ft).

Each of the terms in this equation is statistically significant.

Table E.1—Average Measured Emission Factors for Crude Oil Ballasting

Category	Number of Compartments	Arithmetic Mean	Standard Deviation	Minimum Value	Maximum Value
Category 1	38				
P_{VA} (psia)		3.76	1.648	1.30	8.40
U_A (ft)		2.71	1.475	0.90	5.00
E_B (lb/1000 gal)		1.21	0.740	0.22	4.30
Category 2	16				
P_{VA} (psia)		4.80	2.327	1.65	8.40
U_A (ft)		19.91	11.862	5.80	44.50
E_B (lb/1000 gal)		2.11	1.256	0.51	3.87

Table E.2—Calculated Estimates of Emission Factors and Confidence Intervals for Crude Oil Ballasting

		90 % Confidence Intervals for Mean E_B (lb/1000 gal)	
Category	Mean E_B (lb/1000 gal)	Single Compartment	Average of 100 Compartments
1	1.22	0.45 to 3.29	1.02 to 1.47
2	2.23	0.57 to 8.63	1.56 to 3.17

This correlation was used to predict total emission factors for each category, using the average true vapor pressure of 4 psia and the typical U_A values for each category, 2 ft and 20 ft, respectively, for Categories 1 and 2. For these values, confidence intervals were calculated. These results are shown in Table E.3. It can be observed, by comparing the confidence intervals in Table E.2 and Table E.3, that the use of the correlation provides a better estimate of the total ballasting emissions than the use of average emission factors.

Table E.3—Predicted Estimates of Emission Factors for Crude Oil Ballasting and Confidence Intervals for Average P_{VA} and U_A Values

		90 % Confidence Intervals for Mean E_B (lb/1000 gal)	
Category	Mean E_B (lb/1000 gal)	Single Compartment	Average of 100 Compartments
Category 1 P_{VA} = 4 psia U_A = 2 ft	1.20	0.24 to 2.15	1.00 to 1.39
Category 2 P_{VA} = 4 psia U_A = 20 ft	1.87	0.91 to 2.83	1.65 to 2.09

All supporting data and the procedures used to calculate the average ballasting emission factors, the correlation, and the confidence intervals are in the API Documentation File for Annex E.

Annex F

Evaporative Cargo Loss Estimates

F.1 Sources of Evaporative Cargo Loss

Evaporative cargo loss occurs whenever a liquid cargo evaporates, regardless of whether or not that vapor is displaced from the compartment and emitted into the atmosphere. Evaporation and, thus, cargo loss, occurs whenever a volatile liquid comes into contact with air (or an inert gas) that is not saturated with hydrocarbon vapor. This occurs primarily during loading and discharge operations for noninerted vessels, operating at essentially atmospheric pressure. Other operations, such as manual tank gaging and vessel transit, result in relatively negligible losses. This judgment is based on estimating typical breathing losses, assuming operating pressure/vacuum valves, and calculating losses from tank clingage, based on empirical clingage factors. Therefore, total evaporative cargo loss for vessels operated at atmospheric pressure can be estimated by summing the losses that occur during loading and discharge.

Evaporative cargo loss is only one component of an overall custody transfer loss assessment. Other aspects of cargo measurement and accounting generally have greater significance in the overall accountability of marine cargo transfers.

F.1.1 Evaporative Cargo Loss During Loading

Cargo loss occurs during loading as the stock being loaded comes into contact with the air in the compartment, which is typically not saturated with hydrocarbon vapor prior to loading. This loading loss is equivalent to the generated component of emissions, which is only part of the total loading emissions. Rough estimates of cargo loss during loading can therefore be made by determining the generated part of the total loading emission factor and multiplying this factor by the total volume of cargo loaded.

For crude oil, this generated loss factor can be determined from Equation (A.2). If the vapor pressure of the crude oil is not known, a typical generated loss factor of 0.3 lb/1000 gal loaded can be used for estimating purposes. This factor is based on a crude oil true vapor pressure of 4 psia and a vapor molecular weight of 58 lb/lb-mole.

For gasoline loading, typical generated loss factors of 0.7 lb/1000 gal loaded for tanker loading and 1.7 lb/1000 gal loaded for barge loading can be used to roughly estimate the evaporative cargo loss. These factors are based on data for which the gasoline true vapor pressure averaged approximately 8 psia.

F.1.2 Evaporative Cargo Loss During Discharge

Cargo loss occurs in all cargo compartments during discharge as air is drawn into the compartment and contacts the liquid surface. The hydrocarbon vapor formed during discharge can subsequently be emitted to the atmosphere if ballast water is loaded into the compartment. Rough estimates of cargo loss during discharge can therefore be made by multiplying the appropriate ballasting emission factor by the total amount of cargo discharged.

This technique does not provide a precise measure of cargo loss. Some of the hydrocarbon emitted during ballasting was present in the tank prior to discharge and therefore does not represent additional cargo loss. In addition, evaporative cargo loss should vary with changes in the rate of cargo discharge and the amount of heel left in the tank after discharge, although these factors cannot be quantitatively assessed. Nevertheless, this technique does provide a reasonable rough estimate of evaporative cargo loss during discharge.

For crude oil discharge, typical discharge loss factors are 1.2 lb/1000 gal for fully-loaded tankers and 1.9 lb/1000 gal for lightered or short-loaded tankers. These values are based on a true vapor pressure of 4 psia and a cargo ullage prior to dockside discharge of 2 ft and 20 ft, respectively.

For gasoline discharge, no ballasting emission data are available. However, for rough estimating purposes, estimates can be made by prorating the crude oil factors by the ratio of gasoline to crude oil values for the arrival component of the total loading emission factors. This approach results in gasoline discharge loss factors of approximately 1.9 lb/1000 gal for tankers and 2.2 lb/1000 gal for barges.

F.2 Summary of Volumetric Evaporative Cargo Loss Factors

Based on the discussion in F.1, typical estimates of volumetric percentage loss have been calculated and are summarized in Table F.1. Due to the many assumptions in developing these typical loss factors, it is not possible to quantify the expected accuracy or precision of these estimates. These loss factors should therefore be considered as rough estimates that can be expected to vary from one application to another, as illustrated by example in Table F.2. These estimates are based on typical vapor pressures (4 psia for crude oil and 8 psia for gasoline) and vapor molecular weights (58 lb/lb-mole for crude oil and 63 lb/lb-mole gasoline).

Table F.1—Volumetric Evaporative Cargo Loss Factors

Stock/Vessel	**Typical Loss Factors** (vol %)
Crude oil tankers	
Nonlightered	0.03
Lightered	0.05
Gasoline tankers	0.05
Gasoline barges	0.08

Table F.2—Examples of Predicted Crude Oil Evaporative Cargo Loss Factors

Crude Oil Vessel Operation	P_{VA} (psia)	M_V (lb/lb-mole)	**Estimated Loss** (vol %)
Nonlightered	1	70	0.01
	1	40	0.02
	4	58	0.03
	7	70	0.04
	7	40	0.08
Lightered	1	70	0.01
	1	40	0.02
	4	58	0.05
	7	70	0.07
	7	40	0.12

Loss during discharge accounts for approximately 80 % to 90 % of the total loss factors given in Table F.1 for crude oil and approximately 55 % to 75 % of the barge and tanker gasoline factors, respectively.

The volumetric loss factors are dependent upon cargo vapor pressure and vapor molecular weight. Although vapor pressure is often known or can be reasonably estimated, the molecular weight of the vapor is generally not known. Field measurements during crude oil emission tests have shown that the molecular weight of the vapor varies considerably from one test to another. The observed range was from 34 lb/lb-mole to 74 lb/lb-mole. Interestingly, the extreme values resulted from crude oils with approximately equal Reid and true vapor pressures and gravities. No correlation between vapor molecular weight and crude oil properties could be developed. Much less variability was observed in the gasoline tests. Therefore, although the loss factors given in Table F.1 can serve as typical rough estimates, the volumetric evaporative cargo loss from a given crude oil operation can be determined with greater confidence if the vapor molecular weight is measured. The loss correlation presented in F.3 can then be used.

F.3 Evaporative Cargo Loss Correlation for Crude Oil

A correlation to determine evaporative cargo loss factors for crude oil as a function of true vapor pressure and vapor molecular weight is developed as follows.

As discussed in F.1, the total evaporative cargo loss (in volume percent) is estimated by summing the losses during loading and discharge (in pounds per 1000 gal) and dividing by the density of the condensed vapor (in pounds per gallon) and converting to a percentage value.

From Annex D, the loading loss factor is given below as a function of true vapor pressure and for average values of the other parameters:

$$E_G = 0.205\,[0.44\,(P_{VA}) - 0.42] \tag{F.1}$$

where

E_G is the generated emission factor (lb/1000 gal loaded);

P_{VA} is the true vapor pressure of loaded crude oil (psia).

From Annex E, the discharge loss factor is given by:

$$E_B = 0.31 + 0.20\,(P_{VA}) + 0.01\,(P_{VA})\,(U_A) \tag{F.2}$$

where

E_B is the total ballasting emission factor (lb/1000 gal);

P_{VA} is the true vapor pressure of discharged crude oil (psia);

U_A is the true ullage prior to dockside discharge (ft).

The density of the condensed vapor can be expressed as a function of the vapor molecular weight:

$$W_V = 0.08\,(M_V) \tag{F.3}$$

where

W_V is the density of condensed vapor (lb/gal);

M_V is the vapor molecular weight (lb/lb-mole).

By assuming that true vapor pressure is roughly constant for discharge and loading, Equation (F.1), Equation (F.2), and Equation (F.3) can be combined to yield the following equation for total evaporative cargo loss, L, in volume percent:

$$L = \frac{0.275 + 0.363(P_{VA}) + 0.013(P_{VA})(U_A)}{M_V} \tag{F.4}$$

For nonlightered vessels $(U_{\mathrm{A}} \approx 2\ \mathrm{ft})$, Equation (F.4) simplifies to:

$$L = \frac{0.275 + 0.363(P_{\mathrm{VA}})}{M_{\mathrm{V}}} \tag{F.5}$$

For lightered vessels $(U_{\mathrm{A}} \approx 20\ \mathrm{ft})$, Equation (F.4) simplifies to:

$$L = \frac{0.275 + 0.623(P_{\mathrm{VA}})}{M_{\mathrm{V}}} \tag{F.6}$$

Equation (F.5) and Equation (F.6) can be used with a measured crude oil vapor molecular weight and an average crude oil true vapor pressure to calculate volumetric evaporative cargo loss estimates. To show the sensitivity of these equations to variations in true vapor pressure and vapor molecular weight, calculated loss factors are given in Table F.2 for values of these parameters that span the range of true vapor pressures and vapor molecular weights typically encountered.

For the examples shown in Table F.2, the loss during discharge accounts for roughly 75 % to over 95 % of the total evaporative loss. Specific loading and discharge loss factors can be calculated separately from Equation (F.1) and Equation (F.2), respectively, divided by Equation (F.3) and converted to a percentage loss factor.

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