Manual of Petroleum Measurement Standards Chapter 19.1

Evaporative Loss From Fixed-Roof Tanks

FOURTH EDITION, OCTOBER 2012

AMERICAN PETROLEUM INSTITUTE

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Measurement Coordination

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Summary of Changes to API MPMS Chapters 19.1, 19.2 and 19.4

The third edition of API Manual of Petroleum Measurement Standards (*MPMS*) Chapter 19.4 was published following a revision that was carried out concurrently with revisions to Chapter 19.1, published as the fourth edition, and Chapter 19.2, published as the third edition. Primary changes are:

1) Consolidation of common material in Chapter 19.4. Material that had previously been included in both Chapters 19.1 and 19.2 has been moved to Chapter 19.4. Chapter 19.4, which was previously *Recommended Practice for Speciation of Evaporative Losses*, now has the title *Evaporative Loss Reference Information and Speciation Methodology.* This Chapter had already contained reference information on the properties of chemicals and typical petroleum liquids, and this information has now been removed from Chapters 19.1 and 19.2. In addition, meteorological data have been moved from Chapters 19.1 and 19.2 to Chapter 19.4. In the revised documents:

   a) Meteorological data are found in Chapter 19.4,

   b) Calculation of storage tank temperatures is found in Chapters 19.1 and 19.2 (in that fixed-roof tanks involve calculation of the vapor space temperature in order to determine vapor density, whereas this step is not involved in estimating emissions from floating-roof tanks), and

   c) Calculation of true vapor pressure is found in Chapter 19.4 (in that this is now calculated in the same manner for both fixed- and floating-roof tanks).

2) Reconciliation of nomenclature. Chapters 19.1 and 19.2 previously had different nomenclature for the same variables. These revisions adopt a common set of symbols for both chapters.

3) Reorganization of the formats. In addition to common material having been removed from Chapters 19.1 and 19.2, the remaining text has been edited to remove unnecessarily verbose or repetitive language. The summary tables were deemed redundant, and have been deleted.

4) Appendices. Appendices have been redesignated as annexes.

5) SI units. An annex has been added to each chapter to address SI units.

Chapter 19.1, fourth edition

In addition to common reference material being deleted from Chapter 19.1, the following changes have been made:

1) Reference to API Technical Reports. References to API TR 2568 (cleaning storage tanks) and API TR 2569 (closed vent IFRTs) have been added.

2) Terminology. The following terminology has been revised:

   a) "Standing storage loss" has been changed to "standing loss."

   b) "Solar insolation" has been changed to "insolation."

3) Effective Throughput. An expression has been added for the sum of changes in liquid level, designated ΣH_Q, for calculating effective throughput.

4) Normal operating pressure. An expression has been added for calculating the normal operating pressure, as the average of the maximum and minimum vent settings.

5) Vapor density from vapor space temperature. The temperature used in the calculation of vapor density has been changed from the liquid surface temperature to the vapor space temperature, and an equation has been added for determining the vapor space temperature.

Contents

Chapter 19.1—Evaporative Loss From Fixed-Roof Tanks

1 Scope

This standard contains methodologies for estimating the total evaporative losses of hydrocarbons from fixed-roof tanks. The methodologies provide loss estimates for general equipment types based on laboratory, test-tank and field-tank data.

Types of fixed-roof tanks and roof fittings described are for information only.

The equations estimate average annual losses from uninsulated fixed-roof tanks for various liquid stocks, stock vapor pressures, tank sizes, meteorological conditions, and operating conditions.

The following special cases are addressed:

a) Horizontal tanks.

b) Higher volatility stocks (true vapor pressure greater than 0.1 psia).

c) Vent settings higher than 0.03 psia (0.5 oz/in^2).

The estimation may be improved by using detailed field information, including climatic data and operational data for the appropriate time period.

The equations are not intended to be used in the following applications:

a) To estimate losses from unstable or boiling stocks or from petroleum liquids or petrochemicals for which the vapor pressure is not known or cannot readily be predicted (to calculate emissions from tanks that contain material at or above their boiling point or the point at which material starts to flash, the API model E&P Tank (API Publication 4697) can be used).

b) To estimate losses from fixed-roof tanks which have an internal floating roof. API *MPMS* Ch. 19.2[4] and API TR 2569[13] address these.

c) To estimate losses from fixed-roof tanks which have either roof or shell insulation.

d) To estimate losses from cleaning fixed-roof tanks. API TR 2568[12] addresses this.

The estimation procedures were developed to provide estimates of typical losses from fixed-roof tanks that are properly maintained and in normal working condition. Losses from poorly maintained tanks may be greater. Because the loss equations are based on equipment conditions that represent a large population of tanks, a loss estimate for a group of fixed-roof tanks may be more representative than a loss estimate for an individual tank.

Evaporative loss considerations are not the only criteria for equipment selection. Many other factors not addressed in this standard, such as tank operation, maintenance, and safety, are important in designing and selecting tank equipment for a given application.

2 Normative References

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

API *Manual of Petroleum Measurement Standards* (*MPMS)* Chapter 19.4, *Recommended Practice for Speciation of Evaporative Losses*, 3rd Edition, 2012

3 Symbols

Symbol	Description	Units	Source
B	vapor pressure constant	°R	19.4 Table 3
D	tank diameter	ft	Eq. 3a, 3b
D_H	cylindrical diameter of a horizontal tank	ft	user
D_V	cylindrical diameter of a vertical tank	ft	user
ΣH_Q	annual sum of the increases in liquid level	ft/yr	user
H_L	average liquid height	ft	Eq. 5a, 5b
H_{LN}	minimum liquid height	ft	user
H_{LX}	maximum liquid height	ft	user or Eq. 25
H_R	domed tank roof height	ft	user
H_{RO}	roof outage (or shell height equivalent to the volume under the roof)	ft	Eq. 6a through 6f
H_S	tank shell height	ft	user
H_{VO}	vapor space outage (or height)	ft	Eq. 4a, 4b
I	daily total insolation on a horizontal surface	Btu/(ft^2 day)	19.4 Table 1
K_B	vent setting correction factor	dimensionless	Eq. 27a, 27b
K_C	product factor	dimensionless	Eq. 26a through 26c
K_E	vapor space expansion factor	1/day	Eq. 13a through 13c
K_N	turnover factor	dimensionless	Eq. 23a, 23b
K_S	vented vapor saturation factor	dimensionless	Eq. 7
L_H	end-to-end length, horizontal tanks	ft	user
L_S	standing loss	lb/yr	Eq. 2
L_T	total loss	lb/yr	Eq. 1
L_W	working loss	lb/yr	Eq. 21
M_V	stock vapor molecular weight	lb/lb-mole	19.4 Section 4.5
N	stock turnover rate	turnovers/yr	Eq. 24a, 24b
P_A	atmospheric pressure at the tank site	psia	user
P_{BN}	breather vent minimum pressure setting (negative if a vacuum setting)	psig	user
P_{BX}	breather vent maximum pressure setting (always positive)	psig	user
ΔP_B	breather vent pressure setting range	psi	Eq. 18
P_{VA}	stock true vapor pressure at the daily average liquid surface temperature	psia	4.2.4
P_O	normal operating pressure	psig	Eq. 28
P_{VN}	stock true vapor pressure at the daily minimum liquid surface temperature	psia	4.2.5b)
P_{VX}	stock true vapor pressure at the daily maximum liquid surface temperature	psia	4.2.5b)
ΔP_V	daily stock vapor pressure range	psi	Eq. 15a, 15b
Q	stock throughput	bbl/yr	user
R	ideal gas constant (10.731)	psia ft^3/(lb-mole °R)	
S_R	tank cone roof slope	dimensionless	user
T_{AA}	average daily ambient temperature	°R	Eq. 9
T_{AN}	average daily minimum ambient temperature	°R	Eq. 11
T_{AX}	average daily maximum ambient temperature	°R	Eq. 10
T_B	average liquid bulk temperature	°R	user or Eq. 12
T_{LA}	average daily liquid surface temperature	°R	Eq. 8
T_{LN}	average daily minimum liquid surface temperature	°R	Eq. 16
T_{LX}	average daily maximum liquid surface temperature	°R	Eq. 17
T_{MAX}	average daily maximum ambient temperature	°F	19.4 Table 1
T_{MIN}	average daily minimum ambient temperature	°F	19.4 Table 1
T_V	average vapor temperature	°R	Eq. 20
ΔT_V	average daily vapor temperature range	°R	Eq. 14
V_Q	stock throughput associated with increasing the liquid level in the tank	ft^3/yr	Eq. 22a, 22b

Symbol	Description	Units	Source
W_V	stock vapor density	lb/ft^3	Eq. 19
α	tank surface solar absorptance	dimensionless	19.4 Section 4.8
π	constant (3.14159)	dimensionless	–
NOTE 1 "19.4" refers to API *MPMS* Ch. 19.4, 3rd Edition. NOTE 2 The term "average" refers to average over the period (i.e. year) being considered.			

Abbreviations for units

bbl	barrels
Btu	British thermal units
ft	feet
lb	pounds
psia	pounds per square inch absolute
psig	pounds per square inch gauge
°F	degrees Fahrenheit
°R	degrees Rankine
yr	year

4 Procedure for Estimating Loss

4.1 General

The total loss L_T (lb/yr) is the sum of the standing loss L_S and the working loss L_W:

$$L_T = L_S + L_W \tag{1}$$

where

L_S (lb/yr) is determined in 4.2;

L_W (lb/yr) is determined in 4.3.

4.2 Standing Loss L_S

4.2.1 Aboveground and Underground Tanks

a) For aboveground tanks, the standing loss L_S (lb/yr) is:

$$L_S = 365(\pi D^2/4)\ H_{VO}\ K_S\ K_E\ W_V \tag{2}$$

where

D, H_{VO}, K_S, K_E, and W_V are determined in 4.2.2 through 4.2.6, respectively;

The constant 365 has units of days/yr.

b) For underground tanks, assume no standing loss occurs (L_S = 0) because the insulating nature of the earth limits the diurnal temperature change.

4.2.2 Tank Diameter D

The tank diameter D (ft) is:

a) For vertical tanks,

$$D = D_V \tag{3a}$$

where D_V is the cylindrical diameter of a vertical tank (ft).

b) For horizontal tanks,

$$D = \sqrt{\frac{4L_H D_H}{\pi}} \tag{3b}$$

where

L_H is the end-to-end length of a horizontal tank (ft);

D_H is the cylindrical diameter of a horizontal tank (ft).

4.2.3 Vapor Space Outage H_{VO}

The vapor space outage H_{VO} (ft), the height of a cylinder of diameter D whose volume equals the vapor space volume of a fixed-roof tank, is:

a) For vertical tanks (see Figure 1):

$$H_{VO} = H_S - H_L + H_{RO} \tag{4a}$$

where

H_S is the tank shell height (ft);

H_L is the average liquid height (ft);

If H_L is unknown, use $H_L = (H_{LX} + H_{LN})/2$ (5a)

where

H_{LX} is maximum liquid height (ft);

H_{LN} is minimum liquid height (ft) (height of remaining heel when emptied).

If H_{LX} or H_{LN} is unknown, use $H_L = H_S /2$ (5b)

H_{RO} is the roof outage (ft), the shell height equivalent to the volume contained under the roof.

1) For flat roofs: $H_{RO} = 0$ (6a)

2) For cone roofs: $H_{RO} = H_R /3$ (6b)

where $H_R = S_R D_V /2$ (6c)

If the roof slope S_R is unknown, use: $H_{RO} = D_V /96$ (6d)

(this assumes the roof slope is $^3/_4$ in. on 12 in.).

3) For dome roofs: $H_{RO} = H_R/2 + 2H_R^3/(3D_V^2)$ (6e)

If the roof height H_R is unknown, use $H_{RO} = 0.0686D_V$ (6f)

(this assumes the roof radius equals the tank diameter).

b) For horizontal tanks:

$$H_{VO} = \pi D_H /8 \tag{4b}$$

where D_H is the cylindrical diameter of a horizontal tank (ft).

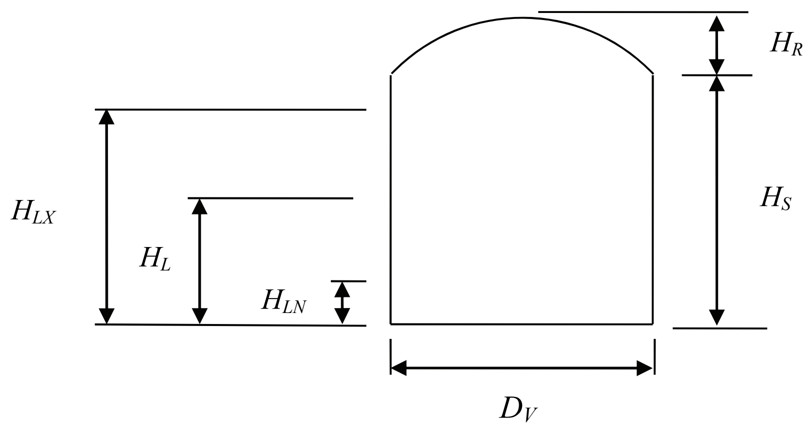

Figure 1 — Fixed-Roof Tank Geometry

4.2.4 Vented Vapor Saturation Factor K_S

The vented vapor saturation factor K_S (dimensionless) accounts for the degree of stock vapor saturation in the vented vapor:

$$K_S = 1/(1 + 0.053 P_{VA} H_{VO}) \tag{7}$$

where

H_{VO} is determined in 4.2.3;

The constant 0.053 has units of 1/(psia-ft).

P_{VA} is the stock true vapor pressure (psia) at the average liquid surface temperature T_{LA}

(use API *MPMS* Ch. 19.4, 3rd Edition, Section 4.2 to determine vapor pressure P_V at a given temperature T)

where

T_{LA} is the daily average liquid surface temperature (°R), which may be determined as follows:

$$T_{LA} = 0.44 T_{AA} + 0.56 T_B + 0.0079 \alpha I \tag{8}$$

$$T_{AA} = (T_{AX} + T_{AN})/2 \tag{9}$$

$$T_{AX} = T_{MAX} + 459.67 \tag{10}$$

T_{MAX} is the daily maximum ambient temperature (°F), obtained from meteorological records or from historical averages given in API *MPMS* Ch. 19.4, 3rd Edition, Table 1.

$$T_{AN} = T_{MIN} + 459.67 \tag{11}$$

T_{MIN} is the daily minimum ambient temperature (°F), obtained from meteorological records or from historical averages given in API *MPMS* Ch. 19.4, 3rd Edition, Table 1.

The constant 0.0079 has units of °R ft^2 day/Btu.

T_B is the liquid bulk temperature (°R), preferably obtained from tank records.

The equation below for estimating liquid bulk temperature is based on the assumption that the product is in thermal equilibrium. The time required for the liquid bulk to achieve thermal equilibrium with ambient conditions, however, would result in the stock typically not being in thermal equilibrium for much of the storage period. Therefore, it is highly preferable to use measured values for the liquid bulk temperature. If measured values are unavailable, T_B may be estimated as:

$$T_B = T_{AA} + (6\alpha - 1) \tag{12}$$

where

α is the tank surface solar absorptance (see API *MPMS* Ch. 19.4, 3rd Edition, Section 4.8);

I is the daily total insolation on a horizontal surface (Btu/(ft^2 day)) (see API *MPMS* Ch. 19.4, 3rd Edition, Table 1);

The constants 6 and 1 have units of °R.

When possible, meteorological data for the tank site should be used. If site-specific data are not available, meteorological data from the nearest weather station may be used. Data for selected U.S. locations are listed in API *MPMS* Ch. 19.4, 3rd Edition, Table 1.

Alternatively, if sufficient data are available, API *MPMS* Ch. 19.4, 3rd Edition, Appendix I may be used for a slight improvement in the estimate of T_{LA}.

4.2.5 Vapor Space Expansion Factor K_E

The vapor space expansion factor K_E is nominally dimensionless but is assigned units of (1/day) because it describes the expansion of vapors in the vapor space that occurs due to the diurnal temperature cycle, and thus it pertains to a daily event.

a) For stocks with $P_{VA} \leq 0.1$ psia and $\Delta P_B \leq 0.063$ psi (see Equation 18), the vapor space expansion factor K_E (1/day) is approximately:

$$K_E = 0.04 \tag{13a}$$

K_E may be estimated more accurately for this case as follows:

$$K_E = 0.0018 \Delta T_V \tag{13b}$$

where

The constant 0.0018 has units of 1/°R.

ΔT_V is the daily vapor temperature range (°R), which may be determined as follows:

$$\Delta T_V = 0.72(T_{MAX} - T_{MIN}) + 0.028\alpha I \tag{14}$$

where

T_{MAX} and T_{MIN} are determined in 4.2.4;

The constant 0.72 is dimensionless; the constant 0.028 has units of (°R ft^2 day)/Btu.

Alternatively, if sufficient data are available, API *MPMS* Ch. 19.4, 3rd Edition, Appendix I may be used for a slight improvement in the estimate of ΔT_V.

b) For stocks with $P_{VA} > 0.1$ or ΔP_B > 0.063 psi (see Equation 18):

$$K_E = \frac{\Delta T_V}{T_{LA}} + \frac{\Delta P_V - \Delta P_B}{P_A - P_{VA}} \geq 0 \tag{13c}$$

where

P_{VA} is determined in 4.2.4;

ΔT_V is determined in 4.2.5a);

T_{LA} is determined in 4.2.4;

$\Delta P_V - \Delta P_B$ is the daily exceedance (psi) of the vapor space pressure range beyond the vent setting range;

ΔP_V is the daily stock vapor pressure range (psi), and may be determined using either of the following methods:

1) $\Delta P_V = P_{VX} - P_{VN}$ (15a)

where

P_{VN} is the stock true vapor pressure (psia) at the daily minimum liquid surface temperature T_{LN}

(use API *MPMS* Ch. 19.4, 3rd Edition, Section 4.2 to determine vapor pressure P_V at a given temperature T)

$$T_{LN} = T_{LA} - 0.25\Delta T_V \tag{16}$$

where

T_{LA} is determined in 4.2.4;

ΔT_V is determined in 4.2.5a);

The constant 0.25 is dimensionless.

P_{VX} is the stock true vapor pressure (psia) at the daily maximum liquid surface temperature T_{LX}

$$T_{LX} = T_{LA} + 0.25\Delta T_V \tag{17}$$

The constant 0.25 is dimensionless.

2) A less accurate method for estimating ΔP_V is:

$$\Delta P_V = 0.5 B P_{VA}(\Delta T_V)/T_{LA}^2 \tag{15b}$$

where

B is the vapor pressure constant for the stock (°R). Only the B constant from the two-constant vapor pressure equation that has units of °R and psia is suitable for use in Equation 15b. (See API *MPMS* Ch. 19.4, 3rd Edition, Table 3.);

P_{VA} is the stock true vapor pressure (psia) at the daily average liquid surface temperature T_{LA} (use API *MPMS* Ch. 19.4, 3rd Edition, Section 4.2 to determine vapor pressure P_V at a given temperature T);

ΔT_V is determined in 4.2.5a);

T_{LA} is determined in 4.2.4.

$$\Delta P_B = P_{BX} - P_{BN} \tag{18}$$

where

P_{BX} is the breather vent maximum pressure setting (psig) (always positive)

If P_{BX} is unknown, assume P_{BX} = 0.03 psig;

P_{BN} is the breather vent minimum pressure setting (psig) (negative if a vacuum setting)

If P_{BN} is unknown, assume P_{BN} = –0.03 psig.

If the fixed-roof tank is of bolted or riveted construction in which the roof or shell plates are not gas tight, assume $\Delta P_B = 0$, even if a breather vent is used.

P_A is the atmospheric pressure (psia) at the tank site.

If P_A is unknown, assume P_A = 14.7 psia.

If Equation 13c yields a negative value for K_E, use zero as the value of K_E. This results in an estimated standing loss of zero because the vent pressure setting range ΔP_B is sufficiently high to prevent breathing loss for the conditions assumed.

4.2.6 Stock Vapor Density W_V

The stock vapor density W_V (lb/ft^3) is:

$$W_V = \frac{M_V P_{VA}}{R T_V} \tag{19}$$

where

M_V is the stock vapor molecular weight (lb/lb-mole) (See API *MPMS* Ch. 19.4, 3rd Edition, Section 4.5);

P_{VA} is determined in 4.2.4;

$$T_V = 0.8 T_{AA} + 0.2 T_B + 0.008 \alpha I \tag{20}$$

where

T_{AA} is determined in 4.2.4;

T_B is determined in 4.2.4;

The constants 0.8 and 0.2 are dimensionless; the constant 0.008 has units of (°R ft^2 day)/Btu;

The equation for vapor space temperature is reasonable in ambient storage circumstances because the vapor space achieves thermal equilibrium relatively quickly.

Alternatively, if sufficient data are available, API *MPMS* Ch. 19.4, 3rd Edition, Appendix I may be used for a slight improvement in the estimate of T_V.

R is the ideal gas constant (10.731 psia ft^3/(lb-mole $^\circ$R)).

4.3 Working Loss L_W

4.3.1 General

Working loss occurs when the liquid level in the tank increases. The working loss L_W (lb/yr) is:

$$L_W = V_Q\, K_N\, K_C\, K_B\, W_V \tag{21}$$

where V_Q, K_N, K_C, and K_B are determined in 4.3.2 through 4.3.5, respectively, and W_V is determined in 4.2.6.

4.3.2 Net Working Loss Throughput V_Q

The working loss throughput (ft^3/yr) is:

$$V_Q = (\Sigma H_Q)(\pi D^2/4) \tag{22a}$$

where

ΣH_Q is the annual sum of the increases in liquid level (ft/yr). If ΣH_Q is unknown, V_Q can be estimated as:

$$V_Q = 5.614Q \tag{22b}$$

where

Q is the stock throughput (bbl/yr). Use of the stock throughput Q overestimates V_Q if filling and withdrawal occur simultaneously;

The constant 5.614 has units of ft^3/bbl.

D is determined in 4.2.2.

4.3.3 Turnover Factor K_N

The turnover factor (dimensionless) is:

$$K_N = 1 \text{ for } N \leq 36 \tag{23a}$$

$$K_N = (180 + N)/(6N) \text{ for } N > 36 \tag{23b}$$

where

The constant 180 has units of turnovers/yr.

N is the stock turnover rate (turnovers/yr) =

$$\Sigma H_Q /(H_{LX} - H_{LN}) \tag{24a}$$

where

ΣH_Q is the annual sum of increases in liquid level (ft/yr);

For vertical tanks, H_{LX} = maximum liquid height (ft).;

For vertical tanks, H_{LN} = minimum liquid height (ft) (height of remaining heel when emptied);

For horizontal tanks, $H_{LX} = \pi D_H /4$ (25)

For horizontal tanks, $H_{LN} = 0$

If ΣH_Q is unknown, N can be estimated as:

$$N = 5.614Q /(\pi D^2(H_{LX} - H_{LN})/4) \quad (24b)$$

Use of the throughput Q may underestimate K_N if product is pumped into and out of the tank simultaneously.

The constant 5.614 has units of ft^3/bbl.

4.3.4 Product Factor K_C

The product factor accounts for the effect of different stocks on evaporative loss during tank working. The product factor (dimensionless) is:

$K_C = 0.75$ for crude oil stocks (26a)

$K_C = 1.0$ for refined petroleum stocks (26b)

$K_C = 1.0$ for single component petrochemical stocks (26c)

4.3.5 Vent Setting Correction Factor K_B

If the breather vent pressure setting range ΔP_B (determined in 4.2.5b)) is less than or equal to the typical range of ±0.03 psig, $K_B = 1.0$. If ΔP_B is significantly greater than ±0.03 psig:

a) If $K_N \dfrac{P_{BX} + P_A}{P_O + P_A} \leq 1.0$,

$$K_B = 1.0 \quad (27a)$$

where

K_N is determined in 4.3.3;

P_A is the atmospheric pressure at the tank site (see 4.2.5b)2);

P_{BX} is the breather vent maximum pressure setting (see 4.2.5b)2);

P_O is the normal operating pressure (psig) $= (P_{BX} + P_{BN})/2$ (28)

b) Otherwise, the vent setting correction factor (dimensionless) is:

$$K_B = \frac{\dfrac{P_O + P_A}{K_N} - P_{VA}}{P_{BX} + P_A - P_{VA}} \quad (27b)$$

where P_{VA} is determined in 4.2.4.

Equation 27b accounts for vapor condensation before the vents open.

5 Example

5.1 Parameters

Estimate the total annual evaporative loss for a vertical fixed-roof tank with the following parameters.

a) The tank diameter D_V = 100 ft.

b) The shell height H_S = 40 ft.

c) The roof is a cone of unknown slope.

d) The average liquid height is unknown.

e) The maximum liquid height H_{LX} = 39 ft and the minimum liquid height H_{LN} = 1 ft.

f) The tank is painted white and its reflective condition is new.

g) The breather vent pressure setting is 0.03 psig and the breather vent vacuum setting is –0.03 psig.

h) The stock is diesel fuel (No. 2 Fuel Oil).

i) The throughput is 3.0 million bbl/yr.

j) Stock temperature data is unavailable.

k) Site meteorological data are unavailable.

l) The nearest city is Wichita, KS.

5.2 Solution

5.2.1 General

For Wichita, KS, API *MPMS* Ch. 19.4, 3rd Edition, Table 1 gives:

a) The daily maximum ambient temperature $T_{MAX} = 67.5$ °F

$$T_{AX} = T_{MAX} + 459.67 = 67.5 + 459.67 = 527.2 \text{ °R} \quad (10)$$

b) The daily minimum ambient temperature $T_{MIN} = 45.0$ °F

$$T_{AN} = T_{MIN} + 459.67 = 45.0 + 459.67 = 504.7 \text{ °R} \quad (11)$$

c) The average daily insolation I = 1458 Btu/(ft^2 day).

The daily average ambient temperature is:

$$T_{AA} = (T_{AX} + T_{AN})/2 = (527.2 + 504.7)/2 = 516.0 \text{ °R} \quad (9)$$

API *MPMS* Ch. 19.4, 3rd Edition, Table 7 gives solar absorptance α = 0.17 for white paint in new reflective condition.

The liquid bulk temperature T_B may be estimated as:

$$T_B = T_{AA} + (6\alpha - 1) \quad (12)$$

$$T_B = 516.0 + (6(0.17) - 1) = 516.0 \text{ °R}$$

The average liquid surface temperature T_{LA} may be estimated as:

$$T_{LA} = 0.44T_{AA} + 0.56T_B + 0.0079\alpha I \tag{8}$$

$$T_{LA} = 0.44(516.0) + 0.56(516.0) + 0.0079(0.17)(1458) = 518.0\ °\text{R}$$

The average vapor space temperature may be estimated as:

$$T_V = 0.8T_{AA} + 0.2T_B + 0.008\alpha I \tag{20}$$

$$T_V = 0.8(516.0) + 0.2(516.0) + 0.008(0.17)(1458) = 518.0\ °\text{R}$$

The daily range in vapor space temperature is:

$$\Delta\ T_V = 0.72(T_{MAX} - T_{MIN}) + 0.028\ \alpha I \tag{14}$$

$$\Delta\ T_V = 0.72(527.2 - 504.7) + 0.028(0.17)(1458) = 23.1\ °\text{R/day}$$

5.2.2 Standing Loss

API *MPMS* Ch. 19.4, 3rd Edition, Section 4.2 gives the true vapor pressure P_{VA} at the average liquid surface temperature T_{LA}

$$P_{VA} = \exp\left[A - \frac{B}{T_{LA}}\right] = \exp\left[12.101 - \frac{8907}{518.0}\right] = 0.006\ \text{psia}$$

Since the average liquid height is unknown, it is taken as

$$H_L = (H_{LX} + H_{LN})/2 = (39 + 1)(\text{ft})/2 = 20\ \text{ft} \tag{5a}$$

Since the roof slope is unknown, the roof outage is taken as

$$H_{RO} = D_V/96 = (100\ \text{ft})/96 = 1.0\ \text{ft} \tag{6d}$$

The vapor space outage is $H_{VO} = H_S - H_L + H_{RO} = 40 - 20 + 1.0 = 21$ ft (4a)

Since $P_{VA} = 0.006 \leq 0.1$ and $\Delta P_B = 0.03 - (-0.03) = 0.06 < 0.063$,

$$K_E = 0.0018\Delta T_V = 0.0018(23.1) = 0.042/\text{day} \tag{13b}$$

The vented vapor saturation factor is:

$$K_S = 1/(1 + 0.053P_{VA}\ H_{VO}) \tag{7}$$

$$K_S = 1/(1 + 0.053(0.006)(21)) = 0.99$$

The stock vapor density is:

$$W_V = \frac{M_V P_{VA}}{RT_V} \tag{19}$$

$M_V = 130$ lb/(lb-mole) from API *MPMS* Ch. 19.4, 3rd Edition, Table 2

$$W_V = (130)(0.006)/[(10.731)(518.0)] = 0.00014\ \text{lb/ft}^3$$

The standing loss is:

$$L_S = 365\ (\pi D^2/4)\ H_{VO}\ K_E\ K_S\ W_V \qquad (2)$$

$$L_S = (365\ \text{days/yr})(\pi 100^2/4)(\text{ft}^2)\ (21\ \text{ft})\ (0.042/\text{day})(0.99)(0.00014\ \text{lb/ft}^3) = 351\ \text{lb/yr}$$

5.2.3 Working Loss

Since ΣH_Q is unknown, V_Q is estimated as:

$$V_Q = 5.614Q = 5.614(3{,}000{,}000) = 16{,}850{,}000\ \text{ft}^3/\text{yr} \qquad (22b)$$

Since ΣH_Q is unknown, N is estimated as:

$$N = 5.614Q\,/(\pi D^2(H_{LX} - H_{LN})/4) \qquad (24b)$$

$$N = 5.614(3{,}000{,}000)\,/(\pi 100^2(39 - 1)/4) = 56.4\ \text{turnovers/yr}$$

Since $N > 36$,

$$K_N = (180 + N)/(6N) = (180 + 56.4)/(6(56.4)) = 0.70 \qquad (23b)$$

Since the stock is diesel, $K_C = 1.0$ (26b)

Since $K_N \dfrac{P_{BX} + P_A}{P_O + P_A} = 0.70 \dfrac{0.03 + 14.0}{0 + 14.0} = 0.70 \leq 1.0$, $K_B = 1.0$

The working loss is:

$$L_W = V_Q\ K_N\ K_C\ K_B\ W_V \qquad (21)$$

$$L_W = (16{,}850{,}000)(0.70)(1.0)(1.0)(0.00014) = 1651\ \text{lb/yr}$$

5.2.4 Total Loss

The total loss L_T is the sum of the standing loss L_S and the working loss L_W:

$$L_T = L_S + L_W \qquad (1)$$

$$L_T = 351 + 1651 = 2002\ \text{lb/yr}$$

6 Equipment Descriptions

6.1 General

This section describes evaporative loss-related construction features of fixed-roof tanks. Figure 2 shows a typical fixed-roof tank. Fixed-roof tanks are vessels that have a cylindrical shell and a fixed roof. In addition to the shell and roof, the construction features include:

a) Roof fittings that penetrate the fixed roof and serve operational functions.

b) Shell and roof insulation on tanks that store stocks in a heated condition.

c) Shell and roof surface type and condition.

Generic types of these components, which are available in a range of commercial designs, are described in this section. Included in these descriptions are comments on how these features affect evaporative loss, as well as some design and operational characteristics. Other factors, such as tank maintenance and safety, are important in designing and selecting tank equipment, but are outside the scope of this publication.

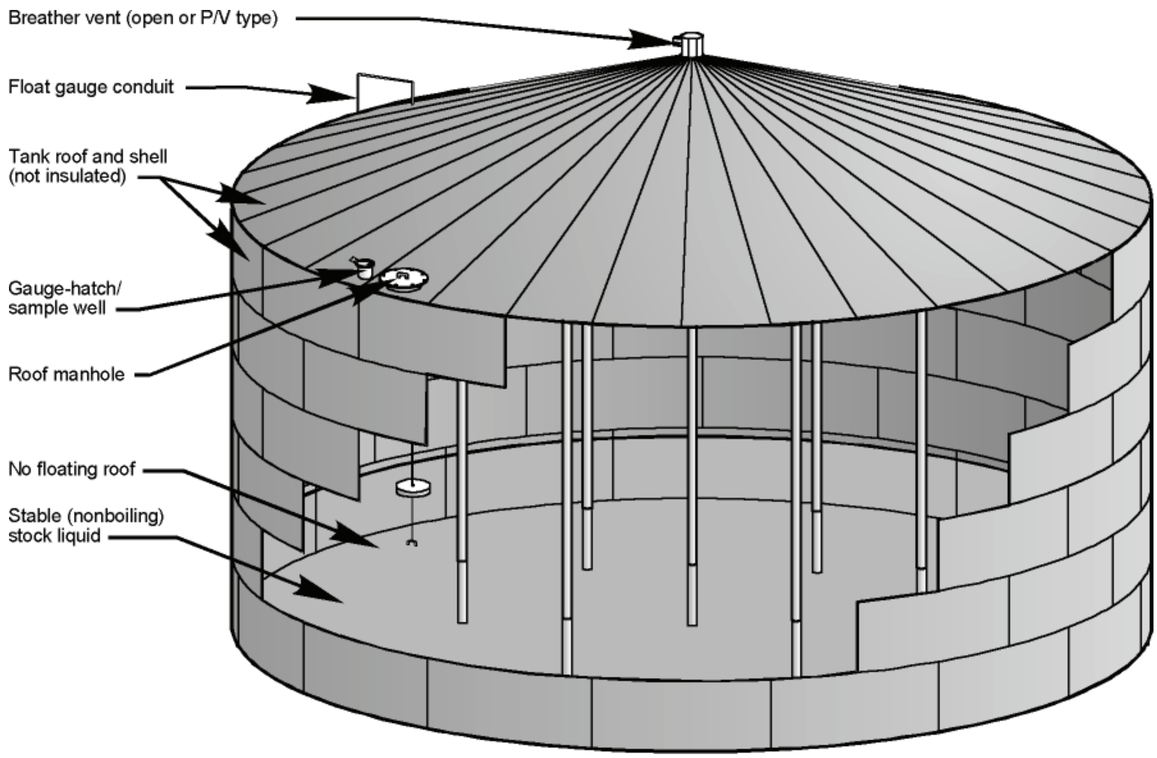

Figure 2 — Typical Fixed-Roof Tank

6.2 Fixed-Roof Tanks

Modern fixed-roof tanks are of welded construction and are designed to be liquid and vapor tight. Some older fixed-roof tanks are of riveted or bolted construction. In this publication, it is assumed that the roof and shell are vapor tight. Tanks range in size up to approximately 300 ft in diameter and 65 ft in height.

API 650[7] provides requirements for atmospheric pressure storage tanks. API 620[6] provides requirements for low-pressure storage tanks.

The fixed roof may be column-supported or self-supported, and may be cone-shaped, dome-shaped, or flat. API 650 specifies the radius of a dome roof be at least 0.8 times the tank diameter but no more than 1.2 times the tank diameter.

6.3 Roof Fittings

6.3.1 General

Roof fittings penetrate the tank roof to allow for operational functions and are potential sources of evaporative loss, in that they may present a path for standing and working losses to exit the tank. Other accessories that are used that do not penetrate the roof or shell are not potential sources of evaporative loss. The most common types of roof fittings used on fixed-roof tanks are described in 6.3.2 through 6.3.5.

The evaporative loss contribution of properly sealed roof fittings is negligible in comparison to the standing and working losses that exit the tank through the roof vents, and thus no contribution to loss from roof fittings other than the roof vents is included in this publication.

6.3.2 Roof Vents

Pressure-vacuum (PV) vents are mounted on the tank roof to provide sufficient venting capacity to protect the tank from experiencing pressure or vacuum greater than the tank design pressure or vacuum, respectively.

When a pressure occurs within the tank vapor space that exceeds the pressure set point, the PV vent opens to release vapors from the tank until the pressure is reduced below its set point. When a vacuum occurs within the tank vapor space that exceeds the vacuum set point, the PV vent opens to admit air into the tank until the vacuum is reduced below its set point.

API 2521[11] describes the use of PV vents on fixed-roof tanks and presents factors to consider in their selection and maintenance. API 2000[8] describes the sizing requirements for PV vents on storage tanks and addresses both normal and emergency venting conditions.

PV vents on atmospheric pressure fixed-roof tanks are usually set at 0.75 inches of water column, or approximately 0.5 oz/in^2. The required normal pressure venting capacity or vacuum venting capacity should accommodate breathing and product movement without exceeding the design pressure or design vacuum of the tank.

Open vents of the mushroom or return-bend (gooseneck) type are sometimes used on fixed-roof tanks storing low-volatility liquids.

6.3.3 Gauge Hatch/Sample Wells

Gauge-hatch/sample wells provide access for manually gauging the stock level in the tank and for taking samples of the tank contents.

Gauge-hatch/sample wells typically consist of a pipe penetration on the tank roof that is equipped with a self-closing cover. Gauge-hatch/sample wells are usually located by the gauger’s platform, which is at the top of the tank shell.

Some vapor loss may occur during manual gauging and stock sampling operations, during which time the gauge-hatch/sample well cover is open. This loss can be minimized by reducing the period of time that the cover is left open.

6.3.4 Float Gauges

Float gauges are used to indicate the stock level in the tank.

Float gauges consist of a float that rests on the liquid surface and is connected to a liquid level indicator mounted outside the tank shell by a cable or tape that passes through a guide system. The cable or tape passes through the tank roof and is normally contained in a sealed conduit.

6.3.5 Roof Manholes

Roof manholes provide access to the tank interior for inspection or maintenance.

Roof manholes normally consist of a circular opening in the tank roof with a vertical neck attached to the roof and a removable cover. The opening is sized to provide for the passage of personnel and materials through the roof.

6.4 Insulation

Some stocks have to be stored in a heated or cooled condition to permit proper handling. Such tanks may require insulated shells and/or roofs, depending upon the local climate, stock properties, and storage temperature.

Insulation can reduce the standing loss by reducing the ambient heat input or loss to the tank. The standing loss estimation procedure described in this publication does not address this and thus overestimates the loss for insulated fixed-roof tanks. Receiving hot stock does not eliminate standing loss, but insulating the tank regardless of whether the stock is heated does reduce standing loss.

6.5 Outside Surfaces of the Tank

Painting the tank shell and roof reduces evaporative loss and preserves the tank. Highly reflective surfaces, such as mill-finish aluminum or surfaces painted white, result in lower tank metal temperatures and lower heat input to the tank, reducing the standing loss. Tank paint inspection and maintenance preserve the paint reflectance and reduce corrosion of the tank. Unpainted aluminum dome roofs provide a highly reflective surface while avoiding the maintenance required for paint.

7 Loss Mechanisms

7.1 General

Evaporation is the natural process in which a liquid is converted to a vapor. Through evaporation, all liquids establish an equilibrium concentration of vapors above the liquid surface. Every liquid stock has a finite vapor pressure that depends on the surface temperature and composition of the liquid and which causes the liquid to evaporate.

Under static conditions, an equilibrium vapor concentration is established, after which no further evaporation occurs. However, fixed-roof tanks are exposed to dynamic conditions that disturb this equilibrium, causing additional evaporation. These dynamic conditions are responsible for continued evaporation, resulting in stock loss and atmospheric emissions.

Evaporation loss from fixed-roof tanks occurs when the evaporated vapor escapes the tank and goes into the atmosphere. The total evaporative loss from a fixed-roof tank is the sum of the standing loss and the working loss.

7.2 Standing Loss

Standing loss is the evaporative loss of stock vapor resulting from the thermal expansion and contraction of the tank air-vapor mixture resulting from the daily heating cycle. This loss is also called breathing loss and occurs without any change in liquid level in the tank.

Several mechanisms are involved in evaporative loss during standing storage. The primary driving force for standing loss from a fixed-roof tank is the daily heating cycle, which usually causes the tank vapor space temperature to increase during daytime hours and decrease during nighttime hours. This heating causes the air-vapor mixture in the tank vapor space to expand and increase in pressure up to the PV vent pressure setting, at which time vapor is vented from the tank vapor space, resulting in evaporative loss. After the vapor space reaches its maximum temperature, which normally occurs in the early afternoon hours, cooling causes the air-vapor mixture in the vapor space to shrink and decrease in pressure. When the pressure falls below the PV vent vacuum setting, air is drawn into the vapor space which then becomes only partially saturated with stock vapor.

During daytime hours, the tank is exposed to ambient heating by both insolation and convective heat exchange with the ambient air. The tank roof is exposed to direct and diffuse insolation, as well as to convective heat exchange with the ambient air. The sunny-side of the tank shell is exposed to direct, diffuse, and ground-reflected insolation, as well as convective heat exchange with the ambient air. The shady-side of the tank shell is exposed to diffuse and ground-reflected insolation, as well as convective heat exchange with the ambient air. During the night, the tank roof and shell exchange heat by convective heat transfer with the ambient air, there being no insolation. This daily heating cycle causes the tank roof and shell to vary in temperature and exchange heat with the air-vapor mixture in the tank vapor space.

During the daily heating cycle, the air-vapor mixture in the tank vapor space exchanges heat with the tank roof interior surface, tank shell interior surface, and the stock liquid surface. This heat transfer causes convective motion of the air-vapor mixture in the tank vapor space.

Also during the daytime when the tank vapor space is heated, some heat is transferred to the liquid surface causing it to increase in temperature, resulting in a higher stock vapor pressure at the liquid surface. As the liquid surface temperature increases during the daily heating cycle, additional stock evaporates, increasing the concentration of vapors above the liquid surface.

Evaporation occurs at the liquid surface as the stock liquid tries to establish equilibrium conditions with the air-vapor mixture in the tank vapor space. Stock vapor evaporated from the liquid surface mixes with the air-vapor mixture and is convected upward toward the vent area by the convection currents that are induced during the daily heating cycle. Also, diffusion of stock vapor occurs from the liquid surface to the tank vapor space. At the top of the tank vapor space, stock vapor mixes with the air which was drawn into the tank vapor space through the PV vent during the prior daily heating cycle. The combined effects of convection and diffusion affect the degree of saturation that occurs at the top of the tank vapor space.

The combined effect of the above loss mechanisms results in movement of stock vapor from the liquid surface to the area below the PV vent, and eventually through the PV vent as the pressure exceeds the PV vent pressure setting. The degree of saturation in the vented vapor depends upon the mass transfer rate of stock vapor from the liquid surface to the top of the tank vapor space by convection and diffusion. These mechanisms typically result in vapor stratification, with the vapor concentration being lowest at the top of the tank vapor space and approaching saturation at the liquid surface.

7.3 Working Loss

7.3.1 General

Working loss is the evaporative loss of stock vapor resulting from an increase in liquid level in the tank. While working loss includes both filling loss and emptying loss, it is sometimes referred to as filling loss.

7.3.2 Filling

Filling loss occurs during an increase in liquid level in the tank, when the air-vapor mixture in the tank vapor space is compressed and causes the pressure in the tank to exceed the PV vent pressure setting, expelling vapors from the tank. The volume of liquid entering the tank displaces an essentially equal volume of air-vapor mixture from the tank vapor space.

The degree of saturation in the vented vapor depends upon the time interval between the tank filling process and the prior tank emptying process, during which period of time the stock tried to establish equilibrium conditions in the tank vapor space.

The method of estimating working loss prior to the 3rd Edition of API *MPMS* Ch. 19.1[2] assumed that the tank behaves as if freely vented during the tank filling process. In other words, the method assumed that the air-vapor volume displaced from the tank equals the liquid volume entering the tank. This assumption is reasonable for very low breather vent settings (such as the typical level of 0.5 oz/in^2). As breather vent settings increase, however, the freely-vented assumption may overestimate working loss. When the breather vent pressure setting is sufficiently high, significant pressure may occur in the vapor space before the vent opens. Vapors begin to condense if pressure in the vapor space increases after saturated conditions are achieved, thereby reducing the volume of vapors released to the atmosphere. The vent setting correction factor K_B accounts for the condensation that may occur with higher vent settings.

7.3.3 Emptying

As the stock liquid level decreases during tank emptying, the pressure in the tank vapor space decreases. When the pressure reaches the PV vent vacuum setting, air enters the tank vapor space through the PV vent. Stock vapors do not escape the tank during emptying, because the direction of any flow through the vents is from outside to inside. The fresh air drawn into the tank induces additional evaporation of stock vapors. These vapors are accounted for in the saturation levels assumed in the working loss turnover factor K_N and the standing loss saturation factor K_S. There is not, however, a separate contribution to stock vapor loss that takes place during emptying of the tank.

During a rapid emptying process, the volume of stock removed from the tank is approximately equal to the volume of air entering the tank vapor space. Stock evaporated from the liquid surface moves upward by convection and diffusion and mixes with the air which has entered the tank vapor space. The rate at which the stock vapor tends to saturate the entering air during tank emptying may partially reduce the volume of entering air. As discussed in 7.2, these mechanisms tend to result in stratification of vapors in the tank vapor space.

8 Development of Estimation Methods

8.1 General

The topic of API *MPMS* Ch. 19.1 was first addressed by API Bulletin 2518, *Evaporation Loss from Fixed-Roof Tanks*, 1st Edition, June 1962[10]. The standing loss equation was improved in the 2nd Edition of API 2518 (also identified as API *MPMS* Ch. 19.1, 2nd Edition, dated October 1991[1]). The 3rd Edition of API *MPMS* Ch. 19.1, dated March 2002[2], included the same equations as the 2nd Edition, but provided:

a) A simplified calculation procedure for estimating emissions for the common scenario of a low volatility liquid (i.e. true vapor pressure $\leq$ 0.1 psi) stored in a fixed roof tank with vents that are either open or have very low set points [i.e. $\leq$ 0.03 psi (0.5 oz/in^2)].

b) A method to estimate emissions from horizontal tanks.

c) A method to account for the vent setting when estimating emissions from tanks with vent settings > 0.03 psi (0.5 oz/in^2) (the 2nd Edition accounted for the vent setting when estimating standing loss, but did not account for the vent setting when estimating working loss).

d) A method to speciate estimated emissions of individual chemicals from the estimate of total hydrocarbon emissions for a multi-component hydrocarbon mixture.

The changes made in this 4th Edition of API *MPMS* Ch. 19.1 are:

a) The equation for stock vapor density is changed from:

$$W_V = \frac{M_V P_{VA}}{RT_{LA}} \text{ to: } W_V = \frac{M_V P_{VA}}{RT_V}$$

so that the stock vapor density is determined at the average vapor temperature rather than at the average liquid surface temperature (see 4.2.6).

b) An equation for the average vapor space temperature T_V is provided (see 4.2.6) as a function of average ambient temperature, liquid bulk temperature, insolation, and tank surface solar absorptance. No equation for average vapor space temperature was provided in the 3rd Edition of API *MPMS* Ch. 19.1.

c) An equation for normal operating pressure P_O is added:

$$P_O = (P_{BX} + P_{BN})/2$$

d) The calculation of the vapor space outage, H_{VO}, and the turnover factor, K_N, have been adjusted to take into account the effect of a liquid heel remaining when the tank is empty.

e) The following information is moved to API *MPMS* Ch. 19.4, 3rd Edition:

1) Stock properties such as stock vapor molecular weight M_V and the determination of true vapor pressure P_V for a given stock at a given temperature;

2) Meteorological data such as maximum and minimum ambient temperatures and average daily insolation; and

3) Tank properties such as solar absorptance α.

f) The term "standing loss" is used in place of "standing storage loss" or "breathing loss," and the term "insolation" is used in place of "solar insolation."

8.2 Standing Loss

8.2.1 General

The 1st Edition of API 2518 issued in June 1962[10] was the result of a study of extensive data on evaporative loss from fixed-roof tanks storing gasoline and crude oil. A standing loss correlation was developed from the data that included stocks with a true vapor pressure between 1.5 and 8.8 psia. Currently, volatile liquids with a true vapor pressure exceeding 1.5 psia are not typically stored in fixed-roof tanks in the U.S. The standing loss estimate presented in the 1st Edition of API 2518 was found to over-predict standing loss for stocks with a true vapor pressure less than 1.5 psia. For this reason, later studies addressed the standing loss by developing a database to provide a standing loss estimation procedure suitable for use over the entire range of true vapor pressures for stocks stored in fixed-roof tanks.

Between 1977 and 1984, three specific testing programs involved measurement of the standing loss from fixed-roof tanks. In 1977, 44 tests were performed on 21 field tanks for the Western Oil and Gas Association (WOGA)[14]. In 1978, 15 tests were performed on six field tanks for the U.S. Environmental Protection Agency (EPA)[15]. In 1984 and 1985, 10 tests were performed on one test tank for API[16].

The test methods utilized to perform these 69 tests were similar for each of the three test programs. This test method involved collecting and measuring the volume of air-vapor mixture that was emitted from the fixed-roof tank during its daily breathing cycle. In addition, the data included stock property data, tank construction data, meteorological data, and tank operating data. Each test was of one-day duration, covering a single breathing cycle.

The 44 WOGA tests[14] were performed on 21 tanks that contained crude oils, distillates, and fuel oils. The tank diameters ranged from 50 to 175 ft, with vapor space outages that ranged from 1.8 to 40.1 ft. The stock true vapor pressure at the daily average liquid surface temperature varied from 0.11 to 4.5 psia. Of the 44 tests, 12 were found suitable for use in developing the vented vapor saturation factor K_S and 8 had sufficiently detailed information to provide a comprehensive comparison with the standing loss equations. In the WOGA tests, the tank vapor space temperature was not measured, so it was not possible to compare the measured and predicted vapor space temperature range.

The 15 EPA tests[15] were performed on six tanks, each containing a separate single component petrochemical that included isopropanol, ethanol, glacial acetic acid, formaldehyde, ethylbenzene, and cyclohexane. The tank diameters ranged from 54 ft to 120 ft, with the vapor space outage varying from 11.4 ft to 27.1 ft. A single temperature probe was used to measure the tank vapor space temperature during the daily heating cycle. Although the amount of tank vapor space temperature data in the EPA tests was not as extensive as it was in the API tests, it provided a valuable check on the vapor space temperature predicted by the API computer model and the standing loss equations. Since the stocks used in each tank in the EPA tests were single component petrochemicals, it was possible to accurately calculate the degree of saturation in the vented vapor during the daily heating cycle. These data provided a valuable basis for developing the vented vapor saturation factor K_S. The stock vapor pressure at the daily average liquid surface temperature in the EPA tests varied from 0.23 to 1.95 psia.

The API tests[16] were performed on a single 20 ft diameter test tank that stored Fuel Oil No. 2. The stock true vapor pressure ranged from 0.0054 to 0.014 psia, with a vapor molecular weight of 110 lb/lb-mole. The tank vapor space outage was 8.85 ft during the entire test series. The vertical temperature distribution inside the tank, extending from below the liquid level upward through the vapor space to the tank roof, was continuously monitored during each test by a series of temperature sensors uniformly positioned on a vertical staff inside the test tank. These temperature measurements included the liquid bulk temperature, liquid surface temperature, vapor space temperature, and metal temperatures on the tank roof and shell. These temperature data provided valuable insight into the convective mixing which occurs in the tank vapor space during the daily heating cycle. Although the API test data was limited to a single tank with a constant liquid level, the extensive amount of tank temperature data and meteorological data permitted a rigorous comparison and validation of the API computer model.

To study the thermal response of a fixed-roof tank, a computer program model was developed[17] that simulated the daily heating cycle. A series of differential equations were solved by step-wise integration over the course of the daily heating cycle to evaluate the thermal response of each of the tank elements including the tank shell, roof, liquid surface, liquid bulk, and vapor space. The computer program was used to develop a computer database that included the predicted standing loss and tank thermal response for a total of 561 sets of conditions that covered a wide range of tank construction, stock properties, and meteorological conditions. When the thermal response and standing loss predicted by the API computer model were compared against the data collected in the API tests[16], excellent agreement was found[18].

Using the API computer database, several proposed loss equations were evaluated[19]. Based on a comparison with the API computer database, a standing loss equation was selected. This loss equation is not a correlation of test data, as was the standing loss equation in the 1st Edition of API 2518[10], but rather is an equation resulting from a theoretical model of the standing loss process.

API *MPMS* Ch. 19.1D[3] Section G contains a sensitivity analysis of the standing loss equation. This sensitivity analysis examined the effect on standing loss of each important variable as it was independently varied over a range of conditions that included a base-case condition.

API *MPMS* Ch. 19.1D[3] Section H contains a comparison of the standing loss equation with the WOGA[14], EPA[15], and API[16] test data. This comparison includes a comparison of the calculated vapor space temperature range, calculated vented gas volume outflow, and calculated daily standing loss with that measured in the tests. The API tests provided an extensive and accurate set of test data for comparison with the API standing loss equation. The average percent difference between the calculated and measured standing loss was 14.3 % for the API test data. The EPA and WOGA test data also confirmed the suitability of the standing loss equation.

8.2.2 Standing Loss Estimate Development

8.2.2.1 Standing Loss Equation

The standing loss equation estimates the annual standing loss simply as the number of days per year times the volume expelled from the tank each day times the density of vapors in the expelled volume. To determine the daily volume expelled, the vapor space expansion factor K_E has to be determined, and to determine the density of the vapors expelled, the vented vapor saturation factor K_S has to be determined.

8.2.2.2 Vapor Space Expansion Factor K_E

The vapor space expansion factor K_E is defined as the ratio of the volume of air-vapor mixture expelled during a daily breathing cycle to the volume of the tank vapor space.

A theoretical equation was developed for the vapor space expansion factor based upon a physical model of the breathing process. This derivation closely followed that originally described in Appendix I of API 2513[9]. The equation derived from the ideal gas law and from the pressure, temperature, and volume conditions that exist in the vapor space of a fixed-roof tank containing a volatile liquid stock during the daily heating cycle.

At sufficiently high vent settings, the breather vent pressure setting range becomes large enough to result in a negative calculated value of K_E. This indicates that the vent settings are so high that the vents will not open during the daily breathing cycle, and the standing loss is therefore zero.

The simplified expressions of Equations 13a and 13b, for approximating the vapor space expansion factor for liquid stocks with true vapor pressure less than or equal to 0.1 psia, assume typical breather vent settings of plus and minus 0.5 oz/in^2 (i.e. ±0.03 psig) and thus a breather vent pressure setting range ΔP_B of 0.06 psi. At higher vent settings, this simplification becomes increasingly conservative (i.e. results in overestimating emissions). The standing loss for these low vapor pressure stocks, however, may be so small that further refinement of the estimate is unwarranted.

The vapor space expansion factor K_E requires an estimate of the vapor space temperature range ΔT_V. A comprehensive heat transfer model of the daily heating cycle provided an analytical equation that was validated by data. API *MPMS* Ch. 19.1D[3] Section C contains the derivation of the vapor space temperature range equation.

API *MPMS* Ch. 19.1D[3] Section A contains the development of the vapor space expansion factor K_E.

8.2.2.3 Vented Vapor Saturation Factor K_S

The vented vapor saturation factor K_S is the ratio of the daily average stock vapor concentration in the vented vapor to the daily average saturated stock vapor concentration. When $K_S = 1$, the vented gas is completely saturated; when $K_S = 0$, the vented gas contains no stock vapor.

Using a theoretical model for the mass transfer of stock vapor from the liquid surface to the PV vent during the daily breathing cycle, a theoretical equation was developed for K_S. This equation contained the pertinent parameters that affect the vented vapor saturation factor K_S. The equation indicated that K_S approaches 1 as the vapor space outage H_{VO} approaches 0. It also indicated that K_S approaches 0 as the stock vapor pressure at the daily average liquid surface temperature, P_{VA}, approaches atmospheric pressure, P_A. The equation contained an overall mass transfer coefficient for the transfer of stock vapor from the liquid surface to the PV vent. Insufficient information was available to evaluate the overall mass transfer coefficient, and thus the theoretical equation provided only a guide to show the dependency of K_S on P_{VA}, H_{VO} and other parameters.

Although it may be possible to develop a more complete theoretical equation for the vented vapor saturation factor K_S it was decided instead to develop a correlation based on actual test data. However, the simplified theoretical equation was used as a guide in selecting the analytical form for the correlation equation and in selecting the parameters to include in the correlation.

The API test data[16], EPA test data[15], and WOGA test data[14] were used to develop the correlation for the vented vapor saturation factor K_S.

The vented vapor saturation factor was calculated for all 10 of the API tests[16]. K_S for the API test data was close to 1, with an average value for the 10 tests of 0.964.

For the 15 EPA tests[15], 12 were found suitable for calculating a vented vapor saturation factor. The daily average liquid surface temperature T_{LA} was not measured during EPA tests; rather, the daily average liquid surface temperature was estimated as $T_{LA} = 0.44T_{AA} + 0.56T_B + 0.0079\alpha I$. This temperature was used for determining the stock vapor pressure at the daily average liquid surface temperature P_{VA}. For the EPA tests, K_S varied from 0.18 to 0.93, depending upon the stock vapor pressure at the daily average liquid surface temperature P_{VA} and vapor space outage H_{VO}.

For the 44 WOGA tests[14], 21 were found suitable for calculating a vented vapor saturation factor. The daily average liquid surface temperature T_{LA} was not measured during the WOGA tests; rather, the daily average liquid surface temperature was estimated as $T_{LA} = 0.44T_{AA} + 0.56T_B + 0.0079\alpha I$. For the WOGA tests, K_S varied from 0.21 to 0.96, depending upon the stock vapor pressure at the daily average liquid surface temperature P_{VA} and the vapor space outage H_{VO}.

A total of 34 data points were selected to develop the vented vapor saturation factor correlation from the combined set of API, EPA, and WOGA test data. The resulting correlation was in agreement with the theoretical analysis in that it showed the same dependency of K_S on P_{VA} and H_{VO}.

API *MPMS* Ch. 19.1D[3] Section B contains both the development of the theoretical equation and the correlation for the vented vapor saturation K_S.

8.2.2.4 Vapor Space Temperature Range ΔT_V

The daily vapor space temperature range ΔT_V is the difference between the daily maximum vapor space temperature and the daily minimum vapor space temperature.

A heat transfer model was developed that described the heat transfer processes which occur during the daily heating cycle. The model was based upon the following assumptions:

a) The gas space is fully mixed (i.e. it is at a uniform temperature at any given time during the daily heating cycle).

b) The liquid remains at a constant temperature during the daily heating cycle.

c) The tank wall in the gas space can be treated as three separate elements: (1) the roof; (2) the half of the tank shell facing away from the sun; and (3) the half of the tank shell facing the sun. Each tank wall element may be characterized by a single temperature, which varies during the daily heating cycle.

d) The effects of rain and snow precipitation are not included in the model.

e) The heat capacity terms in the energy balance equations can be neglected in comparison to the other heat transfer terms.

Using these assumptions, heat balance differential equations were developed for each of the tank wall elements and the gas space. These ordinary differential equations were essentially the same as those used in the API computer model[17], where they were there solved by step-wise numerical integration. Assumption (e) allowed the differential equations to be reduced to a set of four simultaneous algebraic equations, which could be solved for the temperature of the gas space.

The wall elements were assumed to exchange heat on both their inside and outside surfaces. The inside of each element was assumed to exchange heat with the vapor space gas by natural convection heat transfer. The outside of each element was assumed to exchange heat with the ambient air by convection and receive insolation. Certain typical insolation parameters were used (see API *MPMS* Ch. 19.1D[3] Section D for the development of the insolation parameters) to simplify the vapor space temperature range equation. A sensitivity analysis indicated the vapor space temperature range depended little upon the ratio of the outside to inside convection heat transfer coefficients, and an average value was selected for these heat transfer coefficients. The resulting equation was further simplified to the case where the ratio of the tank vapor space outage H_{VO} to tank diameter, D, is 1.0. API *MPMS* Ch. 19.4, 3rd Edition, Appendix I provides a method to account for the effect of tank height-to-diameter aspect ratios in loss estimates.

The simplified heat transfer model was compared[19] with the 561 sets of data in the API computer database[20] and found to result in an average difference of about 4 %.

API *MPMS* Ch. 19.1D[3] Section C contains the development of the vapor space temperature range ΔT_V. API *MPMS* Ch. 19.4, 3rd Edition, Appendix I contains another development of the vapor space temperature range which accounts for the tank-height-to-diameter ratio.

API *MPMS* Ch. 19.1D[3] Section H contains a comparison of the measured and calculated vapor space temperature range for the API, EPA, and WOGA test data.

8.2.2.5 Solar Absorptance α

The solar absorptance α is the fraction of the insolation absorbed by a surface. Information on solar absorptance of various tank surfaces has been moved to API *MPMS* Ch. 19.4, 3rd Edition, since this information is used for both fixed-roof and floating-roof tanks.

8.2.2.6 Liquid Surface Temperature T_{LA}

The standing loss estimate requires determining the stock vapor pressure at the daily maximum liquid surface temperature T_{LX}, the daily average liquid surface temperature T_{LA}, and the daily minimum surface temperature T_{LN}.

In API *MPMS* Ch. 19.1D, a theoretical equation was developed for estimating these liquid surface temperatures that is based on a heat transfer analysis of the liquid during the daily heating cycle. The resulting equations require input of the liquid bulk temperature T_B.

The liquid bulk temperature T_B is the average temperature of the liquid stock in the storage tank. This information is usually available from tank records. If the liquid bulk temperature is not available, it may be estimated from the daily average ambient temperature T_{AA}. API *MPMS* Ch. 19.4, 3rd Edition, Appendix I provides a theoretical method to estimate T_B given T_{AA}, the shell height-to-tank diameter ratio, the insolation, tank construction, and the tank surface solar absorptance α.

The liquid bulk temperature may be estimated solely as a function of daily average ambient temperature and tank solar absorptance by the empirical relationship described in Figure IV-2 in the 1st Edition of API 2518[10]. A linear fit of the data presented in Figure IV-2 from the 1st Edition of API 2518[10] was used, with the assumption that the liquid bulk temperature in a white tank is the same as the average ambient temperature T_{AA}.

API *MPMS* Ch. 19.1D[3] Section F contains the development of the liquid surface temperature equations used in API *MPMS* Ch. 19.1. The development given in API *MPMS* Ch. 19.4, 3rd Edition, Appendix I gives similar results as the development given in API *MPMS* Ch. 19.1D Section F, but accounts for the effect of shell-height-to-diameter ratio on liquid temperatures.

8.3 Working Loss

8.3.1 Working Loss Data

From a survey of petroleum companies and tank builders, working loss data on 123 tanks were compiled. The stock turnover rate N for the 123 tests is summarized below.

Annual Stock Turnover Rate (N) for 123 Test Tanks

N (Turnovers per Year)	Number of Tests
<10	117
10	2
20	1
30	3

Data were collected on numerous items in each test in order to evaluate their effect on the working loss. Variables selected for potential correlation included: measured working loss, stock true vapor pressure (as determined from the stock Reid vapor pressure and the stock liquid bulk temperature), and the turnover rate.

8.3.2 Working Loss Estimate Development

8.3.2.1 Working Loss Equation

The working loss equation in this publication is the same as that which appeared in the 1st Edition of API 2518[10], but with different units. The API 2518 1st Edition equation expressed working loss in terms of bbl/yr, which has been converted to units of lb/yr in this publication. The formula was originally given in Appendix II of API 2513[9].

8.3.2.2 Turnover Factor K_N

The turnover factor K_N is the fraction of saturation in the vented vapor during working loss. The higher the number of turnovers N, the less time that is available for the vapor space to reach saturation. The turnover factor K_N accounts for this non-saturation condition. When $K_N = 1$, the vented vapor is saturated with stock vapor; when $K_N = 0$, the vented vapor contains no stock vapor.

Of the data assembled on 123 working tanks, only 6 tanks exceeded 10 turnovers per year. The remaining 117 tanks had less than 10 turnovers per year. Because so much of the available data was for very low turnover rates, the data were analyzed using the equation given in Appendix II of API 2513[9], which incorporates the turnover factor K_N as a multiplier. When $K_N = 1$, the equation represents the loss resulting from the displacement of a volume of saturated air-vapor mixture by an equal volume of liquid pumped into the tank.

For stock turnover rates N up to 30 turnovers per year, the available test data substantiated a value of $K_N = 1$. No test data were available for turnover rates greater than 30 turnovers per year. Based on a suggested relationship between the turnover factor K_N and the stock turnover rate N published in the API Proceedings, V.32, Part I, 1952, pp. 212–281[21], Equation 23b was developed for high turnover rates (exceeding 36 turnovers per year). This equation results in a value of $K_N = 0.74$ at one turnover per week and $K_N = 0.25$ at one turnover per day.

The 1st and 2nd Editions of API 2518 presented the working loss as:

$$L_W = 0.0010\, M_V\, P_{VA}\, Q\, K_N\, K_P$$

This equation is the same as the working loss equation given in this edition of API *MPMS* Ch. 19.1, except that this equation does not contain a vent setting correction factor K_B, conservatively ignoring any condensation of vapors that may occur prior to the opening of the pressure relief vent. Also, this equation uses Q, the throughput volume in bbl/yr (requiring multiplying by the conversion factor 5.614 ft^3/bbl) and $W_V = M_V P_{VA}/RT$ with $T = 63$ °F (523 °R) as a typical value. The coefficient 0.0010 is the result of the conversion factor 5.614 divided by the fixed temperature value 523 and the ideal gas constant 10.731.

8.3.2.3 Product Factor K_C

The product factor K_C accounts for the effects of crude oil stock on evaporative loss during tank working. These effects (such as weathering) are in addition to those accounted for by considering differences in stock true vapor pressure and vapor molecular weight. In fixed-roof tanks, the product factor applies only to working loss and should not be used to estimate standing loss.

In the 1st Edition of API 2518[10], a product factor of 0.75 was selected for crude oil stocks. The available test data on crude oil working loss were found to be scattered and not sufficiently accurate to permit a formal correlation. However, a review of the scattered data, as well as other considerations, supported a product factor of 0.75 for crude oil. A product factor of 1.0 was assigned to all other stocks. This factor, then, only affects the estimated emissions for crude oil.

When crude oil first enters a tank, the stock is likely to be well-mixed by virtue of the circulation in the tank associated with pumping, and thus the top layer of crude oil would be less likely to be weathered while the tank is standing idle immediately after filling. Correspondingly, the product factor is not applied to standing loss. As time passes, however, the top layer will be increasingly weathered, and the vapor in the vapor space will be associated with a less volatile liquid surface than would be expected from the bulk crude oil. The product factor is associated with filling of the tank and the attendant expulsion of these vapors that are associated with the weathered condition. Correspondingly, the product factor is applied to working loss.

8.3.2.4 Vent Setting Correction Factor K_B

The 1st and 2nd Editions of API 2518 did not include a vent setting correction factor K_B for the estimation of working loss. The method for estimating working loss in those editions assumed that the tank behaves as if freely vented during the tank filling process. This assumption is reasonable for very low breather vent settings (such as the typical level of 0.5 oz/in^2). As the breather vent settings increase, however, the freely-vented assumption becomes increasingly conservative (i.e. it overestimates loss).

The calculation of the vent setting correction factor is performed in two steps. The first step checks whether the compression of the vapor space during filling, prior to opening the vent, is sufficient to bring the concentration of vapors above the saturation point. If the vapor concentration reaches the saturation point, it is assumed that condensation begins to occur. The vapor reduction due to condensation is then calculated using the ideal gas laws as formulated in Equation 27b.

Annex A
(informative)

SI units

Guidelines to convert the U.S. customary units employed in this document to equivalent units of the International System (SI) of Units are given in API *MPMS* Ch. 15[5].

The unit of length is either the kilometer, designated km, or the meter, designated m.

The unit of mass is the kilogram, designated kg.

The unit of volume is the cubic meter, designated m^3.

The unit of time is the year, designated yr.

The unit of temperature is the degree Celsius, designated °C, or the Kelvin, designated K.

The unit of heat energy is the joule, designated J.

The unit of pressure is the kilopascal, designated kPa.

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