Evaporative Loss from Storage Tank Floating Roof Landings

TECHNICAL REPORT 2567
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Measurement Coordination

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FOREWORD

The methodologies presented in this report were presented previously in a January 23, 2002, report, *Tentative Method for Determining Storage Tank Evaporative Losses from Floating Roof Landings*, prepared for API by Robert L. Ferry of The TGB Partnership. The purpose of this revision is to address a scenario that was not addressed in the earlier report. The earlier report addressed storage tanks that retain a heel of stock liquid across the entire bottom of the tank when the floating roof is landed, and storage tanks that are drained dry. This revision addresses the intermediate case of a partial liquid heel, in which pools of stock liquid remain in the tank (and thus it is not drained dry), but the free standing liquid does not cover the entire bottom of the tank. There have been no changes to the equations or factors presented in the earlier report, other than the addition of the case for a partial liquid heel.

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Suggested revisions are invited and should be submitted to API, Standards department, 1220 L Street, NW, Washington, DC 20005, standards@api.org.

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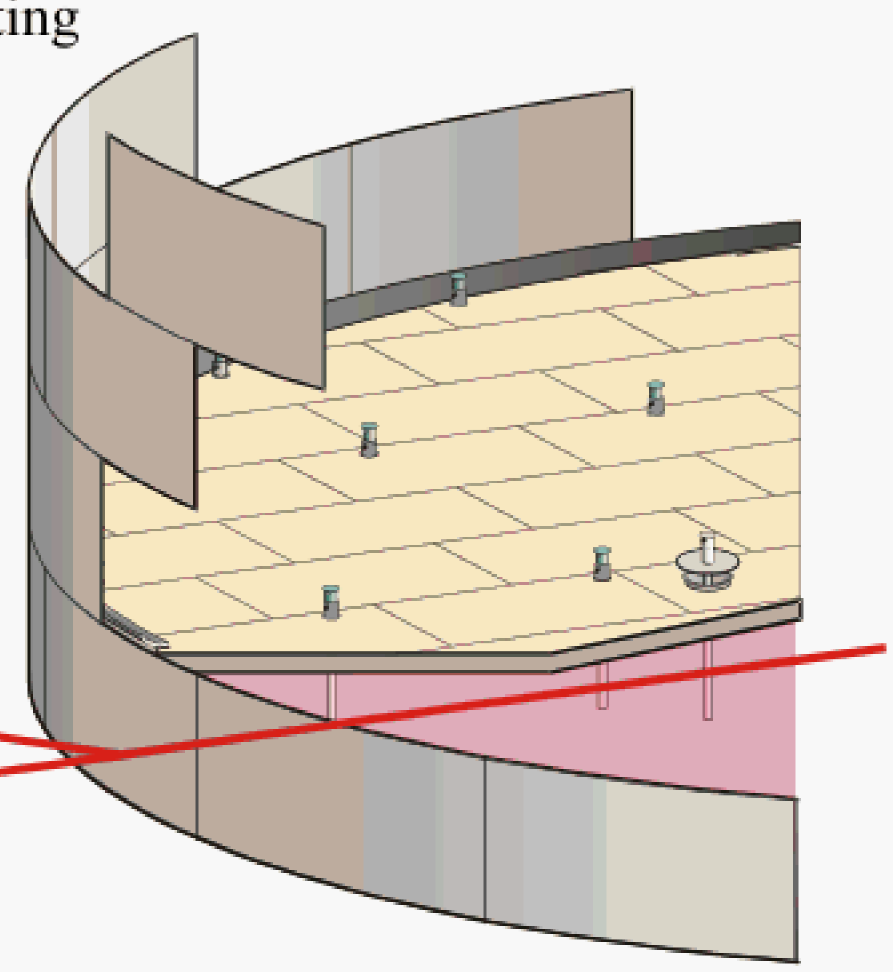
1. EXECUTIVE SUMMARY

1.1 Statement of Purpose

The purpose of this study was to investigate storage tank emissions that may result from landing and subsequently refloating a floating roof. The existing emission factors for floating-roof tanks [1,2] are based on the assumption that the floating roof is continuously floating on the stored stock liquid. Additional emissions may occur, however, if the tank is emptied such that the floating roof is no longer floating.

When the liquid level approaches the bottom of the tank, the floating roof lands on deck legs or other supports which prevent it from dropping any further as the stock liquid continues to be removed. Further withdrawal of stock liquid could then potentially form a partial vacuum beneath the landed floating roof. If the receding liquid were to create an excessive partial vacuum, the floating roof could collapse. To avoid this condition, a vacuum-breaker vent on the floating roof opens automatically as the floating roof lands (see Figure 1 on page 6). The vapor space created under the floating roof is thereby freely vented to the space above the floating roof.



Vapor loss (and the corresponding emissions to the atmosphere) may occur while the tank remains nominally empty and the floating roof continues to stand idle in this landed condition (see Figure 2 – Standing Idle Loss). Additional emissions may occur during the refilling of the tank, as the vapor space beneath the floating roof is displaced by the incoming stock liquid (see Figure 3 – Filling Loss). This study sought to quantify these floating-roof landing loss emissions.

1.2 Summary of the Investigations

Part I of this study proposed a methodology for estimating floating-roof landing losses for tanks storing refined products. Steps pursued in the development of this methodology included a literature search,[1-14] a survey of manufacturers and owners of petroleum storage tanks, computer modeling, and analyses of available emissions data from fixed-roof tank breather vents and from barge loading operations. The results of Part I were presented in the report, *Determining Product Evaporation from Tank Turnovers*,[15] October 1, 1997, prepared for API by Robert L. Ferry and J. Randolph Kissell of The TGB Partnership (TGB).

Data collection for Part II of the study involved field tests that were conducted in 1998 and 1999. Data were obtained from four tanks, each representing a different combination of tank construction and type of stock liquid. It was not economically feasible to test a sufficient number of tanks to empirically determine emission factors for floating-roof landing losses, given the spectrum of construction configurations and storage conditions found in the industry. Furthermore, limitations on accessibility to the space under the floating roof impose constraints on the field methods used. These limitations were found to impact the absolute accuracy of the data gathered.

While it was recognized that the testing of a single tank is insufficient for determining a typical value for the entire population of similar tanks, and that the data gathered should be interpreted as relative indicators rather than as absolute measures, it was expected that comparison of the data from each of the test tanks would indicate relative trends for the different tank configurations. The results of these field tests were presented in the report, *Determining Product Evaporation from Tank Turnovers, Part II - Tank Testing*,[16] May 1999, prepared for API by Sue Sung and Yousheng Zeng of Trinity Consultants.

Part II of the study also included a review by TGB of the methodology proposed in Part I, in light of the field test results and other available data. This review specifically considered the following:

a. whether wind effects should be included in the model,

b. extension of the model to include crude oil, and

c. reasonableness of the model in light of the relative trends exhibited in the field data.

Part III of the study incorporated the results of Parts I and II into a revised model for estimating floating-roof landing losses. This revised model was presented in the January 23, 2002 report, *Tentative Method for Determining Storage Tank Evaporative Losses from Floating Roof Landings*,[17] prepared for API by Rob Ferry of TGB.

API sponsored an additional field study in 2003 that sought to overcome the testing difficulties experienced in the earlier field work. The first step of this study was to develop field and laboratory protocols for measuring the concentration of vapors displaced from under a landed floating roof during the refilling process. These protocols were then applied to obtain data from three internal floating-roof tanks, each of which was in gasoline service. This 2003 field study provided spot validation of the 60% vapor saturation value proposed in the 1/23/02 TGB Report for internal floating-roof tanks with a full liquid heel (see Table 1). The results of the 2003 study were presented in the January 28, 2004 report, *Floating Roof Landing Loss: Field Study of Saturation Factors for Refilling of Internal Floating-Roof Tanks*,[18] prepared for API by Rob Ferry of TGB.

In addition to spot validation of the full liquid heel case, the 2003 study collected samples from tanks for which the liquid heel did not extend across the entire bottom of the tank. The free-standing liquid in these partial liquid heel cases was confined to the area in or near the sump. This case of a partial liquid heel was not addressed in the 1/23/02 TGB Report, in that none of the supporting data were applicable to such a case.

In order to better quantify a saturation level for the case of a partial liquid heel, API commissioned additional testing in 2004. The purpose of the 2004 study was to obtain additional data points, to be combined with the data collected from similar tanks in 2003, in order to develop a saturation factor for the condition of a partial liquid heel. The results of the 2004 study were presented in the November 15, 2004 report, *Floating Roof Landing Loss: Field Study of A Refill Saturation Factor For An IFRT With A Partial Liquid Heel*,[19] prepared for API by Rob Ferry of TGB.

This report retains the methodology presented in the 1/23/02 TGB Report, and adds the case of a partial liquid heel.

1.3 Scope and Limitations of the Model

The emissions characterized as floating-roof landing losses in this study are those that would be expected to occur if a floating roof is landed in the course of normal operations, and subsequently refilled. This study does not address emissions that may result from additional activities, such as degassing or tank cleaning, that may occur while the tank is empty.

The model is intended for use with any petroleum liquid. The inclusion in the model of the stock liquid's physical properties (i.e., true vapor pressure, vapor molecular weight, and liquid density) appears to effectively differentiate crude oil from gasoline, and therefore no further differentiation was made in the form of product factors or other product-specific adjustments.

The model assumes that the stock liquid used to refill the tank is the same as that stored prior to landing the floating roof. Situations in which there is a change of service (i.e., the tank is to be filled with a different stock than it had been storing) may warrant differentiating between the stock vapor properties for the arrival and generated components of filling loss.

The model does not address standing idle losses for partial days. It would be conservative (i.e., potentially overestimate emissions) to apply the model to episodes during which the floating roof remains landed for less than a day.

Any emission factor is properly understood as representative of the actual emission rates that are typical for a population of emission points. For a non-uniform population, however, there is an inherent level of uncertainty associated with the application of the general emission factor to any individual emission point. Some of the critical sources of uncertainty in this model of floating-roof landing losses are addressed in the comments on the confidence associated with each step of the model. As noted in these comments, some of the variables have not been well defined, and the values shown are intended to serve only as placeholders – pending further research.

1.4 Proposed Estimating Methods

Floating-roof tanks were segregated into the following categories for purposes of estimating landing losses:

a. internal floating-roof tanks (IFRTs) with a full or partial liquid heel,

b. external floating-roof tanks (EFRTs) with a full or partial liquid heel, and

c. IFRTs and EFRTs that drain dry.

The two modes of vapor loss (standing idle and filling) are evaluated differently for each of these categories of floating-roof tanks.

1.4.1 Standing Idle Loss.

The first two categories are described as having a liquid heel, which is a reference to stock liquid remaining in the bottom of the tank as it stands idle after having been emptied (see Figure 4). This heel of stock liquid provides a continuing source of vapors to replace those expelled by breathing (in the case of an internal floating-roof tank) or wind action (in the case of an external floating-roof tank). For each of these cases, then, standing idle loss is a process that is repeated on a daily basis.

The third category is described as drain dry, which refers to a tank that is designed to drain its entire bottom to a sump (see Figure 5). The tank's withdrawal line is located in the sump in a manner that leaves virtually no free-standing liquid in the tank after it has been emptied. The only stock liquid available for evaporation, then, is that which clings to the tank bottom and other wetted surfaces under the floating roof. Once this thin film has evaporated, there is no free stock liquid remaining to replenish vapors under the floating roof. Standing idle loss from a drain dry tank does not continue to occur day after day, but rather is limited to a one-time evaporation of the liquid clinging to the wetted surfaces.

A tank only qualifies as a drain-dry tank if all of the free-standing liquid has been removed. If the tank drains to a sump, but a heel of free-standing liquid is left in the sump, then the tank would be considered to have a partial liquid heel. Flat bottom tanks that have most of the free-standing liquid removed by means of a vacuum truck typically have pools of liquid remaining, and should generally be considered to have a partial heel as well.

1.4.2 Filling Loss.

Each of these categories experiences filling loss in addition to the standing idle loss. The filling loss is assumed to include vapors from two sources. The first source is those vapors that remain under the floating roof at the end of the standing idle period. These are the vapors residing in the vapor space immediately prior to the introduction of incoming stock liquid, and are referred to as the arrival component of vapors. Additional vapors are generated by the incoming liquid itself. This source is referred to as the generated component of vapors. Each of these vapor components may be represented by a saturation factor applied to the vapor space volume.

1.4.3 Total Landing Loss.

The total loss for a given floating-roof landing episode is the sum of the standing idle loss and the filling loss, as shown in Equation 1.

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

where:

L_T is the total landing loss per episode (pounds),

L_S is the standing idle loss per episode (pounds), and

L_F is the filling loss per episode (pounds).

1.4.4 Landing Loss Estimation Equations.

Proposed methods for estimating standing idle and filling losses for each of the three categories of tank design are summarized in Table 1. The expressions shown are for estimating the emissions for a single episode of landing the floating roof. An estimate of annual floating-roof landing losses may be obtained by summing the estimated emissions of all the landing episodes that occur during a given year.

Table 1. Summary of Floating-Roof Landing Loss Estimation Methods by Tank Type (per Episode)

	Internal Floating-Roof Tanks with a Liquid Heel	External Floating-Roof Tanks with a Liquid Heel	all Drain-Dry Tanks
Standing Idle Loss	(daily)	(daily)	(one-time event)
Equation	equations 5 & 10	equations 14 & 10	equation 18
	$L_S = n_d\, K_E \left(\frac{P\, V_V}{R\, T}\right) M_V\, K_S$	$L_S = 0.57\, n_d\;D\, P^*\, M_V$	$L_S = 0.0063\, W_l \left(\pi\, D^2 / 4\right)$
	but $\leq 5.9\, D^2\, h_{le}\, W_l$	but $\leq 5.9\, D^2\, h_{le}\, W_l$	but $\leq \left(P\, V_V / R\, T\right) M_V\; S$ using the IFRT value for S
Standing Idle Saturation Factor, K_S	K_S from equation 8. not to exceed S for filling.	not applicable	not applicable
Filling Loss	equation 20	equation 21	equation 20
Equation	$L_F = \left(\frac{P\, V_V}{R\, T}\right) M_V\; S$	$L_F = \left(\frac{P\, V_V}{R\, T}\right) M_V \left(C_{sf}\;\, S\right)$	$L_F = \left(\frac{P\, V_V}{R\, T}\right) M_V\; S$
Filling Saturation Factor, S	$S = 0.60$ for a full heel $S = 0.50$ for a partial heel	but $C_{sf} S \geq 0.15$ using the IFRT value for S and C_{sf} is from equation 23.	$S = 0.15$

Note: Equation 14, for the standing-idle loss of an EFRT, should be regarded as a placeholder. While there are sufficient field and lab data available to demonstrate that wind is a factor in this case, there are not sufficient data to support a particular formulation of the model. In the absence of data, a placeholder was selected that is a relatively simple function of tank diameter, yet yields results that fall within reasonable upper and lower bounds. The other cases lend themselves to derivable theoretical equations, but there are varying degrees of uncertainty in the values assigned to the variables. These uncertainties are discussed in the text of the report.

Where:

L_S is the standing idle loss per episode .... in pounds; .... as calculated per Table 1.

n_d is the number of days the tank stands idle with the floating roof landed .... (dimensionless); .... as specified by the user.

K_E is the vapor space expansion factor .... (dimensionless); .... $= \frac{\Delta T_V}{T}\left(1 + \frac{0.50\, B\, P}{T\left(P_a - P\right)}\right)$ (6)

ΔT_V is the daily vapor temperature range .... in degrees Rankine; .... as calculated from equation 7, or 20°F (= 20°R) if unknown.

T is the average temperature of the vapor and liquid below the floating roof .... in degrees Rankine; .... = avg ambient temperature (°F) + 460.

B is a constant from Antoine's equation ..... in degrees Rankine; .... from Table 2.

P is the true vapor pressure of the stock liquid .... in psia; .... as specified by the user, or Table 2.

P_a is the atmospheric pressure at the tank location .... in psia; .... as specified by the user.

V_V is the volume of the vapor space .... in feet^3; .... $= h_v\, \pi\, D^2 / 4$

h_v is the height of the vapor space under the floating roof .... in feet; .... as specified by the user. *

D is the tank diameter .... in feet; .... as specified by the user.

R is the ideal gas constant .... in psia ft^3 per lb-mole °R; . = 10.731

M_V is the stock vapor molecular weight .... in pounds per pound-mole; as specified by the user, or Table 2.

K_S is the standing idle saturation factor .... (dimensionless); .... $= \frac{1}{1 + 0.053\,(P\, h_v)} \le S$ (8)

S is the filling saturation factor .... (dimensionless); .... as stipulated in Table 1.

P^* is a vapor pressure function .... (dimensionless); .... $= \frac{P / P_a}{\left(1 + \left[1 - \left(P / P_a\right)\right]^{0.5}\right)^2}$ (12)

W_l is the stock liquid density .... in pounds per gallon; .... as specified by the user, or Table 2.

h_{le} is the effective height of the stock liquid .... in feet; .... as specified by the user. *

L_F is the filling loss per episode .... in pounds; .... as calculated per Table 1.

C_{sf} is the filling saturation correction factor . (dimensionless); .... $= 1 - \frac{(equation\ 14) - (equation\ 5)}{(equation\ 5) + (equation\ 20)}$ (23)

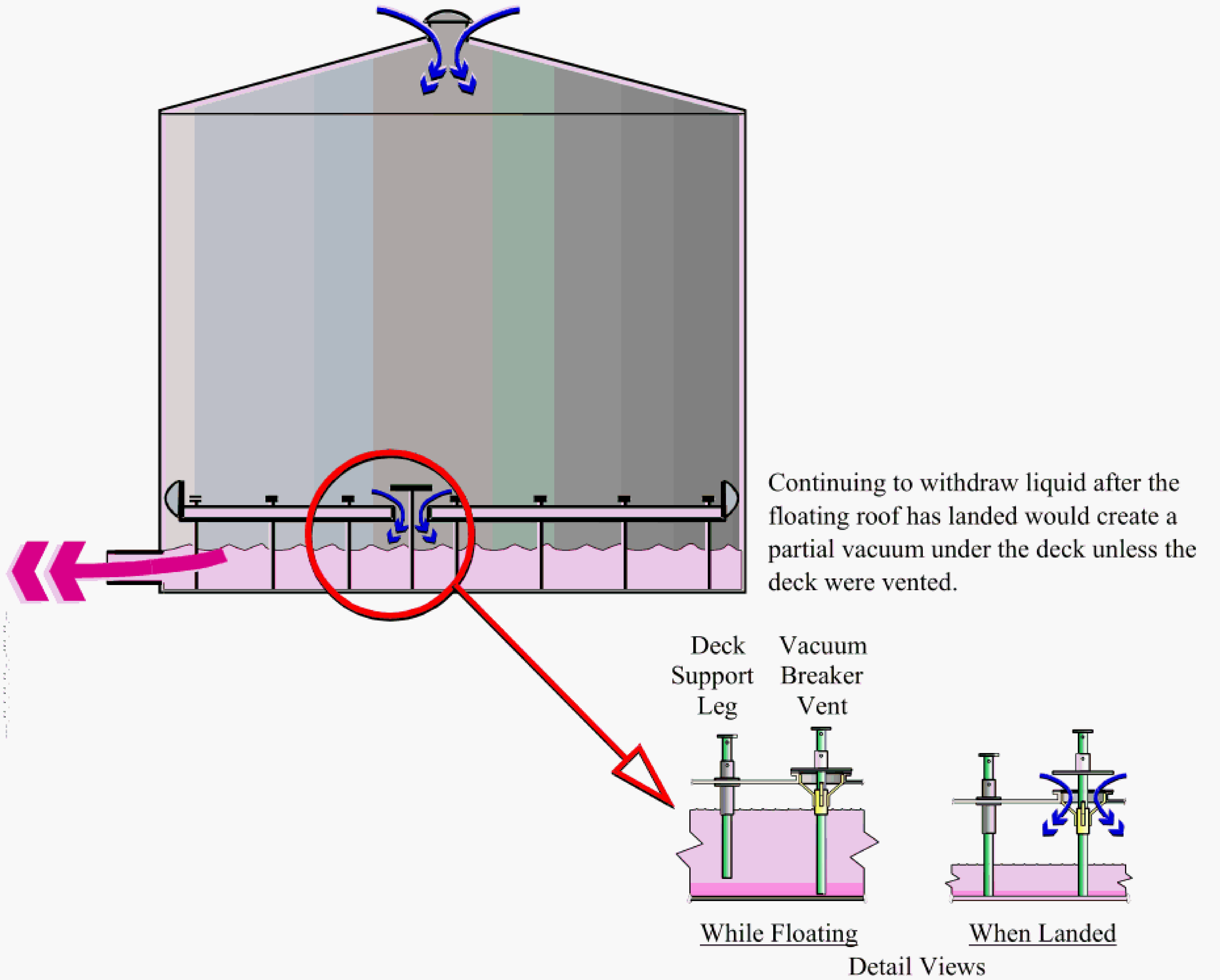
* See section 4 for adjustment to h_v and h_{le} in the case of a cone-bottom tank.

Table 2. Properties of Selected Petroleum Stocks

Petroleum Stock	W_l lb/gal	M_V lb/lb-mole	A dim'less	B dim'less	True Vapor Press, P (psia), at Selected Temps, T (°F) 40	50	60	70	80	90
Motor Gasoline (RVP 13)	5.6	62	11.644	5043.6	4.7	5.7	6.9	8.3	9.9	11.7
Motor Gasoline (RVP 10)	5.6	66	11.724	5237.3	3.4	4.2	5.2	6.2	7.4	8.8
Motor Gasoline (RVP 7)	5.6	68	11.833	5500.6	2.3	2.9	3.5	4.3	5.2	6.2
Jet Naphtha (JP-4)	6.4	80	11.368	5784.3	0.8	1.0	1.3	1.6	1.9	2.4
Jet Kerosene(Jet A)	7.0	130	12.390	8933	0.004	0.006	0.008	0.011	0.015	0.021
Distillate Fuel Oil No.2	7.1	130	12.101	8907	0.003	0.005	0.007	0.009	0.012	0.016

Source: U.S. EPA Report AP-42, Fifth Edition, Supplement D,[2] Table 7.1-2; except the Antoine's equation constants, A and B, are from API MPMS 19.2.[1]

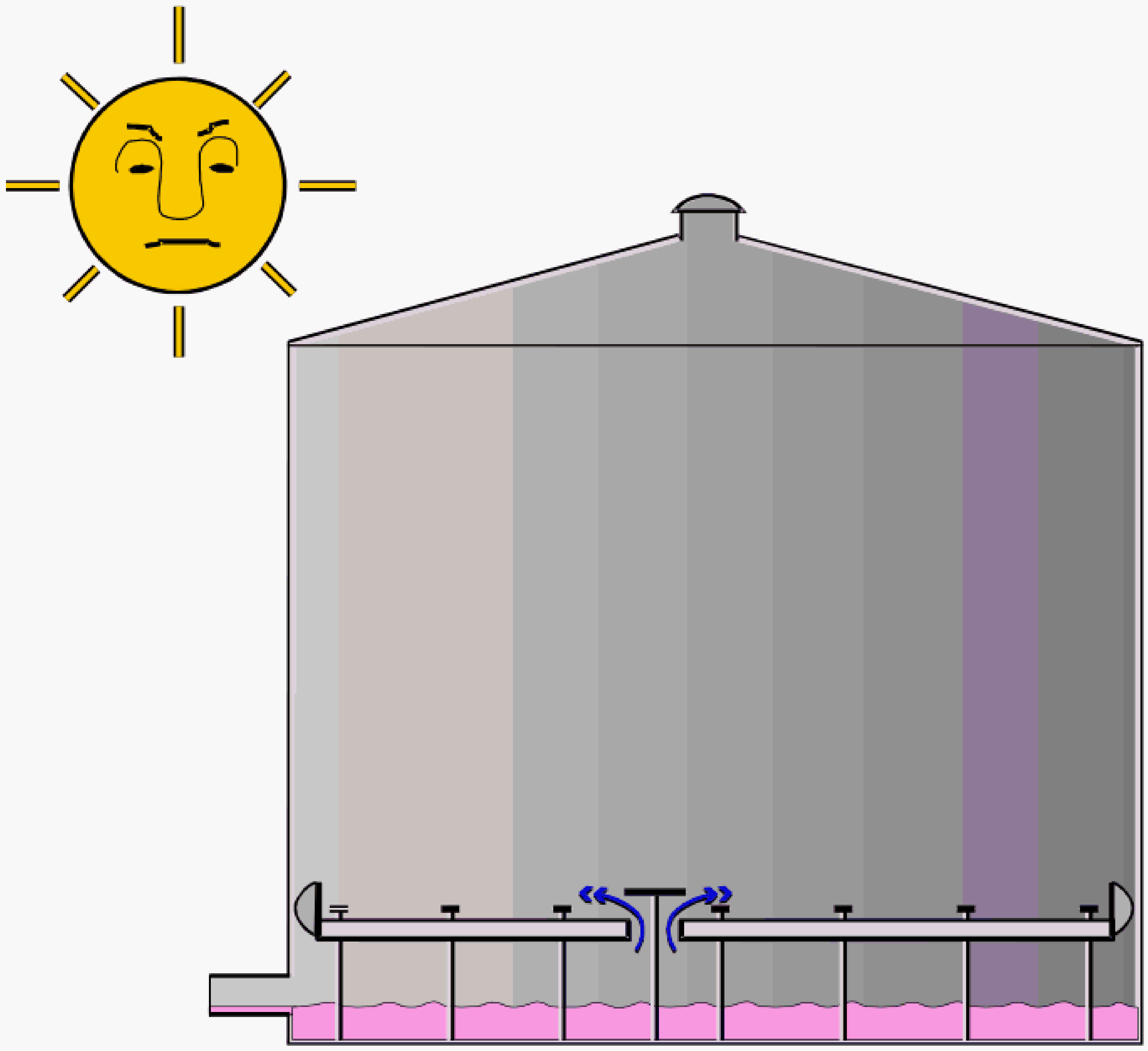
Figure 1. Vacuum-breaker vent.



Leg-actuated type vacuum-breaker vent

As the floating roof descends with the withdrawal of stock liquid, the leg of the vacuum-breaker vent contacts the tank bottom before the deck support legs. The floating roof then continues to descend until coming to rest (landing) on the deck support legs. Because the lid of the vacuum-breaker vent had been fixed in position by the longer vacuum-breaker vent leg, it is lifted off the vacuum-breaker opening by the continued descent of the floating roof.

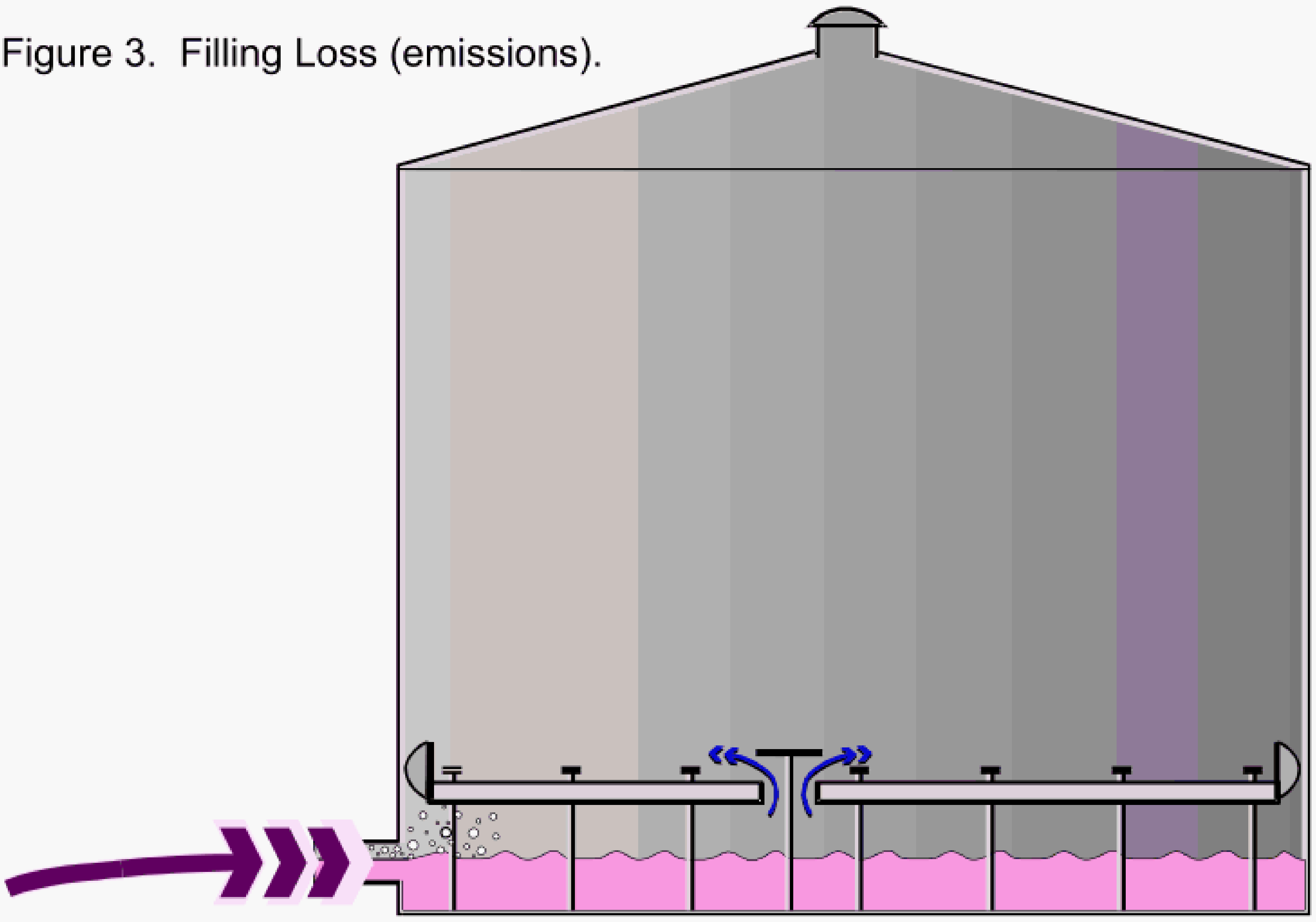
Figure 2. Standing-Idle Loss (emissions).



The headspace above the floating roof is either open to the atmosphere (in the case of an EFRT) or freely vented to the atmosphere (in the case of an IFRT).

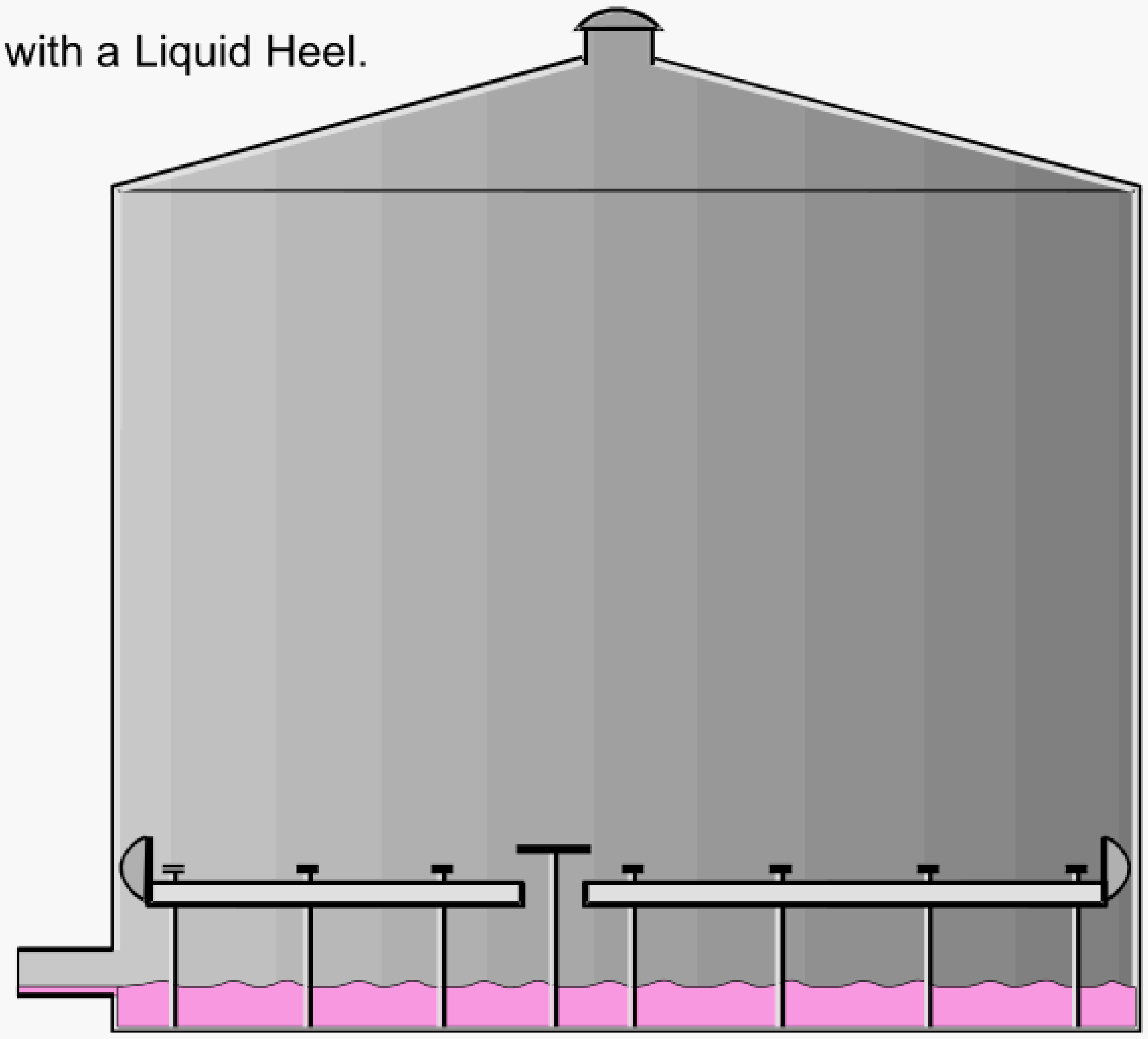
Daily breathing expels vapors from under the floating roof.

Figure 3. Filling Loss (emissions).



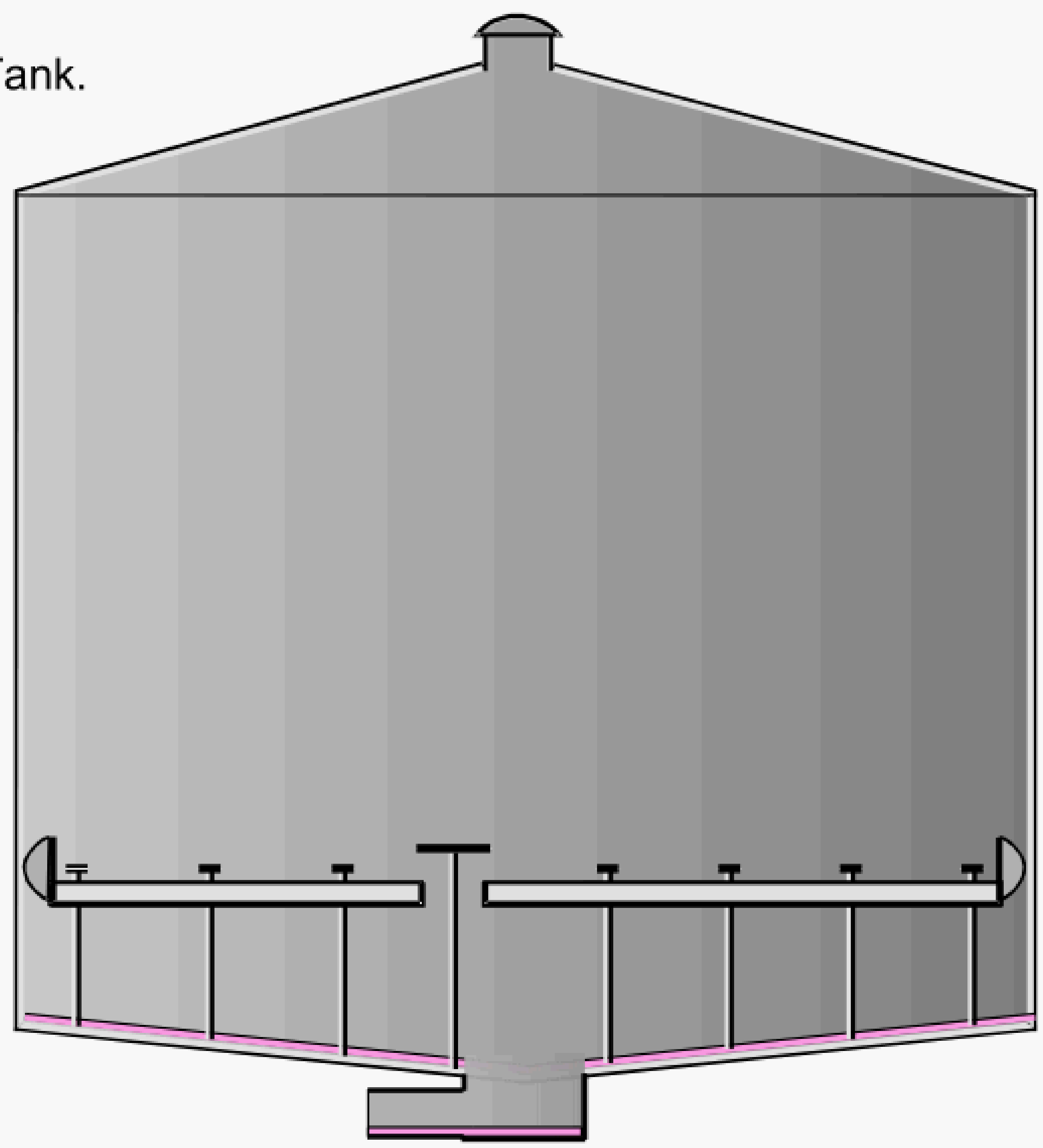
When the tank is refilled, the incoming liquid displaces vapors from under the floating roof.

Figure 4. Tank with a Liquid Heel.



Stock liquid that is below the outlet (withdrawal line) remains in the tank after emptying.

Figure 5. Drain-Dry Tank.



The bottom of a drain-dry tank slopes to a sump, and the withdrawal line is in the sump.

2. DESCRIPTION OF CONCENTRATION AND SATURATION

A quantity of volatile hydrocarbon liquid stored in a vessel would be expected to evaporate into the vapor space above the liquid surface. This evaporation would ideally continue until the partial pressure of the hydrocarbon vapor in the vapor space is in equilibrium with the true vapor pressure of the stock liquid. This is the *saturated* condition.

The *concentration* (by volume) of stock vapors at saturation is equal to the true vapor pressure of the stock liquid, P, divided by the system pressure. For a freely vented vapor space, the system pressure is equal to atmospheric pressure, P_a. The concentration at saturation is then P/P_a.

It has been observed, however, that the vapor space above stored hydrocarbons tends to stratify. The concentration of hydrocarbon vapors approaches P/P_a at the liquid surface, but decreases up through the vapor space. The ratio of the resulting average concentration, y, to the concentration at saturation, P/P_a, is represented by the saturation factor, S:

$$S = \frac{y}{P/P_a} \qquad (2)$$

At saturation, y equals P/P_a, and S equals 1.0. When y is less than P/P_a, the vapor space is not saturated, and the saturation factor, S, is less than 1.0. The saturation factor may also be expressed as a percent, in which case the value determined by equation 2 is multiplied by 100.

When a known or assumed value for the saturation factor is given, the concentration is determined as a function of the true vapor pressure of the stock liquid, by rearranging equation 2.

$$y = \left(\frac{P}{P_a}\right) S \qquad (3)$$

It is evident from equation 3 that, for a given value of the saturation factor, the volume concentration is directly related to the true vapor pressure of the stock liquid.

3. DESCRIPTION OF FLOATING-ROOF LANDING LOSSES

3.1 Landing Loss Events

The emissions associated with each episode of landing a floating roof and subsequently refilling the tank may be categorized as occurring in two distinct events. The first is driven by the evaporation of stock liquid that remains in the bottom of the tank while the floating roof is landed. This event shall be termed *standing idle loss*. The other event is the displacement of stock vapors from under the floating roof when the tank is refilled. This event shall be termed *filling loss*. The total emissions for a given episode are then the sum of the standing idle loss and the filling loss for that episode. To estimate the annual emissions associated with floating roof landings for a particular tank, the emissions per episode would be multiplied by the number of times per year that the floating roof is landed.

Any freely-vented floating-roof tank would be expected to have landing losses if the floating roof is landed, regardless of whether the tank is an internal floating-roof tank (IFRT), external floating-roof tank (EFRT), or a covered (domed external) floating-roof tank (CFRT). The tank construction will, however, influence the estimated magnitude of the landing losses.

Given that floating-roof landing losses occur when a floating-roof tank has been emptied below the level that lands the floating roof, this emission episode does not occur if the floating roof is maintained in a floating condition, nor does it occur with a tank that does not have a floating roof.

3.2 Standing Idle Loss Mechanisms

The loss mechanism assumed for standing idle loss in the 10/1/97 TGB Report was breathing of the vapor space under the floating roof. This mechanism involves the generation of vapors beneath the floating roof by evaporation of liquid remaining in the bottom of the tank, and the subsequent daily expulsion of a portion of these vapors in response to the daytime rise in ambient temperature. As the ambient temperature rises and heats the tank, the vapors expand and a portion of them are pushed out of the vapor space.

The vapors that remain beneath the floating roof are eventually all expelled by incoming liquid when the tank is refilled. Although these vapors are generated while the tank is standing idle, they are included with the filling loss rather than the standing idle loss.

After subsequent consideration, it was concluded that the breathing mechanism model applies only to internal floating-roof tanks with sufficient liquid remaining in the tank to continually replenish vapors lost by daily breathing (i.e., IFRTs with a liquid heel). The standing idle loss mechanism identified for external floating-roof tanks with a liquid heel is wind effects. When a liquid heel is not present because the tank has been drained virtually dry, then the standing idle loss mechanism appears to be the evaporation of the thin layer of liquid clinging to the bottom of the tank. This clingage mechanism applies to drain-dry operations for both internal and external floating-roof tanks.

3.2.1 Internal Floating-Roof Tanks With a Liquid Heel (full or partial).

Standing idle losses from a landed internal floating roof with a liquid heel are modeled as a breathing phenomenon. The vapor space beneath the internal floating roof is assumed to behave in a manner similar to the headspace of a fixed-roof tank. The height of the vapor space beneath the floating roof is substituted for the vapor space outage in the calculation method published in API's *Manual of Petroleum Measurement Standards, Chapter 19.1*[3] (API MPMS 19.1), where this phenomenon is termed *standing storage loss*.

3.2.1.1 Confidence in the Breathing Loss Model. The equation used in this model is derived from the ideal gas laws, and should be a reliable predictor of breathing loss when the variables are evaluated correctly. Required inputs for this equation include temperature data and characteristic saturation levels for given scenarios. The methodology presented in API MPMS 19.1 predicts the liquid surface and vapor space temperatures to be within a few degrees above ambient temperature, with the increase being due to solar insolation. The effect of solar insolation on the space below a landed internal floating roof, however, may be assumed to be insignificant. This space is shaded by both the fixed roof and the internal floating roof, and temperature fluctuations are further mitigated by the tank bottom being in contact with the ground. The temperature of the stock liquid and vapor is likely to be within a few degrees of the ambient temperature when taken as an average over the course of a year for a large tank population, but may vary significantly for an individual tank on a particular day. The accuracy of the model would be improved if the actual temperature below the floating roof were known, in terms of both the daily average temperature and the daily range of temperature.

The greatest uncertainty in the estimation of landing losses from a landed internal floating roof with a liquid heel is perhaps in the saturation level assumed in the model. The model uses the method for calculating the saturation level that is used in API MPMS 19.1 for fixed-roof tanks, with an upper bound imposed to limit the potential to overestimate. As noted in 3.3.1.2, this approach results in the estimated saturation factor while standing idle being equal to or less than that during filling. This is the expected relationship, in that additional vapors may be generated during the filling operation. The development of this variable in the model is discussed in more detail below.

A potential conservatism in the breathing model pertains to the assumption that the vapors expelled by vapor space expansion each day are fully dissipated prior to the nighttime contraction of the air in the vapor space. These expelled vapors, however, are typically heavier than air. Thus, when the vapor space above the floating roof is sufficiently static, the expelled vapors will tend to remain immediately above the deck. Some of these vapors may then be included with the air drawn back under the deck by nighttime cooling. The standing idle loss would therefore be overestimated to the extent that some of the expelled vapors are subsequently drawn back beneath the deck. This same phenomenon would apply to internal floating roofs while they are floating. The existing emissions factors for internal floating roofs assume that there is sufficient air movement inside the tank to prevent any significant concentration of vapors immediately above the deck. In order to maintain consistency with the assumptions inherent in the existing emission factors, this mechanism has been neglected in this study as well.

3.2.1.2 Derivation of the Breathing Loss Model. API MPMS 19.1 presents the following equation for estimating breathing losses from fixed roof tanks:

$$L_S = 365\ V_V\ W_V\ K_E\ K_S \tag{4}$$

where:

L_S is the annual breathing loss during standing storage,

365 is the number of days in a year,

V_V is the volume of the vapor space,

W_V is the stock vapor density

$= (M_V P) / (R\,T)$,

M_V is the stock vapor molecular weight,

P is the true vapor pressure of the stock liquid,

R is the ideal gas constant,

T is the temperature,

K_E is the vapor space expansion factor, and

K_S is the saturation factor.

To render this equation useful for daily estimates, rather than annual, the constant 365 may be replaced with a variable, n_d, for the number of days that the tank stands idle. Making this substitution, as well as substituting for W_V as shown above, yields equation 5:

$$L_S = n_d\ K_E \left(\frac{P\,V_V}{R\,T} \right) M_V\ K_S \tag{5}$$

In equation 5, the term $(P\ V_V) / (R\ T)$ represents the number of moles of stock vapor in the vapor space, at equilibrium conditions (i.e., at saturation). The number of moles is converted to pounds of stock vapor when multiplied by the stock vapor molecular weight, M_V. The portion of these vapors expelled daily by thermal breathing is represented by the variable K_E, the vapor space expansion factor. The variable, n_d, refers to the number of days for which this daily event occurs. The K_S term is the saturation factor (introduced in Section 2 as S), which accounts for the stock vapor concentration being below the saturated condition. Thus a K_E fraction of the vapor space is expelled each of n_d days, with the concentration of stock vapors at a K_S fraction of the saturated condition.

The vapor space expansion factor, K_E, is presented in API MPMS 19.1 in terms of the daily range of the stock vapor pressure, which in turn is shown as a separate calculation. Combining these two equations allows K_E to be expressed as shown in equation 6:

$$K_E = \frac{\Delta T_V}{T}\left(1 + \frac{0.50\, B\, P}{T\left(P_a - P\right)}\right) \tag{6}$$

The term from API MPMS 19.1 for the breather vent pressure setting range does not appear in equation 6, because the vapor space under the internal floating roof is assumed to be freely vented. Values of the Antoine's equation constant, B, may be calculated from API MPMS 19.1, or obtained from Table 2 for selected petroleum stocks. The daily vapor temperature range may be calculated from equation 7, or assumed to be equal to 20°R in the absence of actual data. Either approach may be conservative (i.e., potentially overestimate emissions), in that the shading of the vapor space and its location near to the ground undoubtedly mitigate temperature fluctuations.

$$\Delta T_V = 0.72\left(T_{MAX} - T_{MIN}\right) + 0.028\,\alpha\, I \tag{7}$$

The daily maximum and minimum ambient temperatures, T_{MAX} and T_{MIN}, are for the tank site location during the days that the floating roof is landed. If this information is not known, it may be approximated from the monthly values given in API MPMS 19.1 for selected U.S. cities.

The terms α and I refer to the tank solar absorptance factor and daily total solar insolation factor, respectively. The solar absorptance factor describes the fraction of the incident solar radiant heat that is absorbed by the tank shell and roof. The daily total solar insolation factor describes the typical amount of solar radiant heat that is incident on a horizontal surface at a given locale. API MPMS 19.1 provides values of the solar absorptance factor for a selection of tank surface colors and conditions, and values of daily total solar insolation for selected U.S. cities.

API MPMS 19.1 determines the saturation factor, K_S, for standing idle loss in terms of the true vapor pressure of the stock liquid and the height of the vapor space. Defining h_v as the height of the vapor space, K_S may be calculated as shown in equation 8:

$$K_S = \frac{1}{1 + 0.053\,(P\, h_v)} \tag{8}$$

Stock vapors remaining beneath the floating roof during the standing idle condition constitute one of the two components of filling loss, as discussed further in 3.3. The filling loss saturation factor, S, would therefore establish a conservative upper bound on the standing idle loss saturation factor, K_S.

An additional constraint is added to the standing idle losses from tanks with a liquid heel, recognizing that the total emissions while standing idle cannot exceed the available stock liquid in the tank. This volume may be calculated from the following expression.

$$L_{S\max} = \left[\frac{\pi}{4} D^2\, h_{le}\, W_l \left(7.48 \text{ gallons/ft}^3\right)\right] \tag{9}$$

$$L_{S\max} = 5.9\, D^2\, h_{le}\, W_l \tag{10}$$

where:

$L_{S\max}$ is the limit on standing idle loss, in pounds per landing episode, and

h_{le} is the effective height of the stock liquid, in feet.

3.2.2 External Floating-Roof Tanks With a Liquid Heel (full or partial).

Standing idle losses from a landed external floating roof with a liquid heel are modeled as a wind-driven phenomenon. Whereas the thermal breathing mechanism only expels the volume of vapors corresponding to the vapor expansion factor, K_E, tanks subject to wind action may have vapors flowing from beneath the floating roof at a greater rate (see Figure 6). These wind effects were discussed in the interim report [20] of December 23, 1998, prepared by Rob Ferry of TGB.

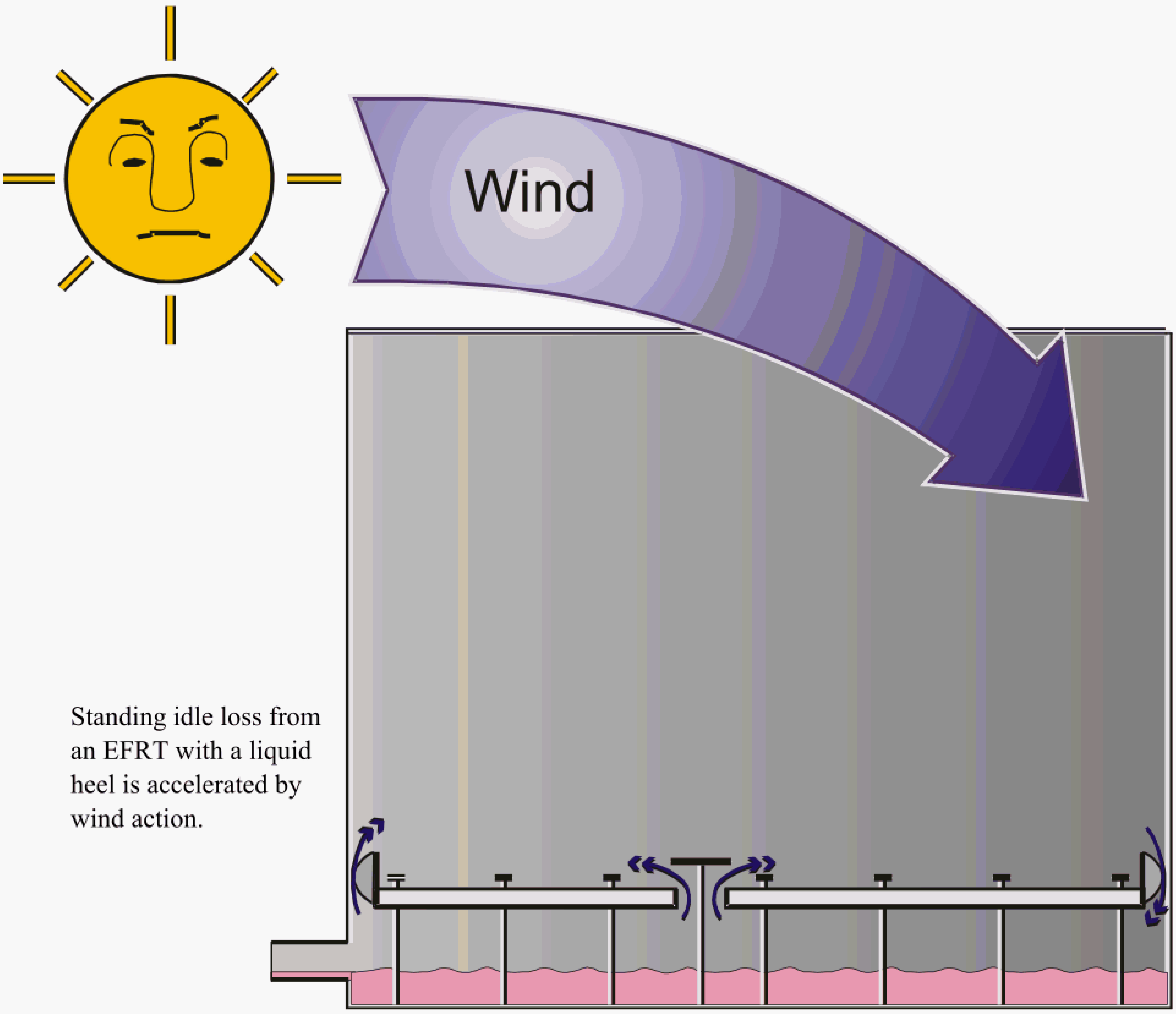


Figure 6. Wind Action

Field testing reinforced the conclusion that vapors are flushed by wind from beneath a landed external floating roof. Test Tanks 1 and 4 were both drain-dry external floating-roof tanks, one storing gasoline and the other storing crude oil. In both cases an initial rise in stock vapor concentration was measured in the vapor space after landing the floating roof, but within a day or two the stock vapors were no longer present. Figure 7 is a plot of the VOC concentration level for Test Tank 1 versus ambient wind speed.

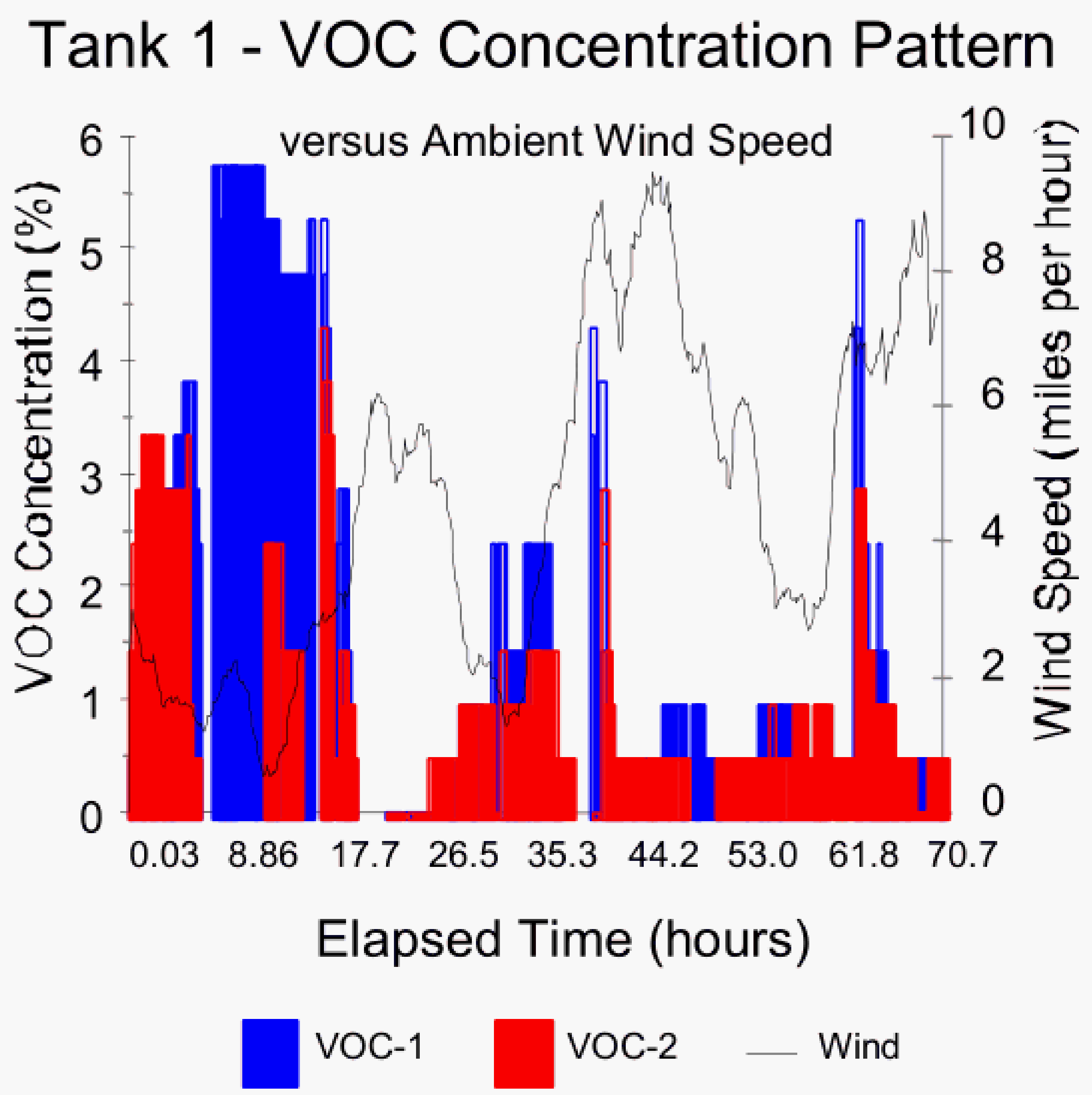


Figure 7. Wind Effects

Figure 7 shows that the stock vapor concentration rose to just under 6 percent during the relatively calm period of the first 18 hours. As soon as the wind speed rose above about 4 miles per hour, however, the stock vapors were completely dissipated. When the wind speed subsequently subsided, an increase in stock vapor concentration was again measured. The next rise in the wind speed eliminated any sustained return of stock vapors (the narrow spikes at about the 40th and 64th hours were dismissed in the Trinity report as resulting from fluctuations in the instrument readings that occur when the stock vapors are at a non-measurable level). A pattern of stock vapor dissipation in response to elevated wind speed is apparent.

3.2.2.1 Confidence in the Wind Effects Model. The equation used to model wind effects should be viewed as a placeholder, rather than as a derived characterization of the actual relationship between ambient wind speed and standing idle losses. While standing idle losses from an external floating-roof tank with a liquid heel appear to be driven by wind, the rate at which these losses occur at a given wind speed is not known. That is, the proposed equation holds a place in the model for addressing the observed phenomenon of wind effects, but there are no data available at this time for characterizing certain variables.

In the absence of data, a placeholder was selected that is relatively simple, with the loss rate expressed as a constant times the tank diameter. While additional data may eventually justify adding terms to the proposed equation, there is no benefit to be gained by adding complexity to the equation without data to demonstrate an improvement in accuracy. The value used for the constant in this placeholder was derived from default values that were selected to generate an estimate that exceeds a rational lower bound. It would not be appropriate, then, to override the default value for one of these terms without data to guide corresponding substitutions for the other terms.

3.2.2.2 Derivation of the Wind Effects Model. The placeholder value in the TGB interim report for the rate of wind-driven standing idle loss was developed in the context of rational upper and lower bounds. The lower bound recognizes that the wind-driven estimate of emissions should never be less than the emissions estimated when wind is neglected.

As an upper bound, the wind-driven estimate of emissions should never exceed the rate that would be estimated for an open pool (i.e., limited only by the rate of evaporation). It was shown in the TGB interim report that this upper bound is unnecessary in the equation, because the emissions estimated by the proposed model are two to three orders of magnitude less than the upper bound case of evaporation from an open pool of stock liquid.

The proposed model calculates emissions as if the external floating roof has a vapor-mounted primary rim seal. Regardless of the rim seal design, the rim seal is rendered 'vapor mounted' while the floating roof is landed and the liquid level is below the bottom of the rim seal. Any benefit of the secondary seal is neglected in order to approximately account for additional vapor loss through the floating-roof deck fittings, and the product factor is taken as 1.0 for all stocks. Rim-seal loss may be estimated by the use of equations 3, 10, and 11 from API MPMS 19.2,[1] yielding the following:

$$L_r = (K_{ra} + K_{rb} V^n) D P^* M_V K_c \tag{11}$$

where:

L_r is the annual rim seal loss,

K_{ra}, K_{rb}, and n are loss factors specific to a given configuration of rim seal,

V is the ambient wind speed,

D is the tank diameter,

P^* is a vapor pressure function

$$= \frac{P/P_a}{\left(1+\left[1-\left(P/P_a\right)\right]^{0.5}\right)^2} \tag{12}$$

P_a is atmospheric pressure,

P is the true vapor pressure of the stock liquid,

M_V is the stock vapor molecular weight, and

K_c is the product factor.

Accounting for the stock properties (i.e., true vapor pressure, vapor molecular weight, and liquid density) in the model appears to reasonably differentiate crude oil from gasoline. The product factor, K_c, in equation 11 is therefore taken as 1.0 for crude oil as well as for refined stocks. Applying the loss factors for a vapor-mounted primary seal, using a default wind speed of 10 miles per hour, and substituting 1.0 for the product factor, equation 11 is simplified as follows:

$$L_r = 210\, D P^* M_V \tag{13}$$

The annual loss is adjusted to a daily loss by the ratio $n_d/365$, yielding the following:

$$L_{S\,\text{wind}} = 0.57\, n_d D P^* M_V \tag{14}$$

This adjustment to the model addresses an increase in the flow rate of vapors from under the floating roof due to wind. While the result of this change is a higher level of estimated standing idle loss for an external floating-roof tank, this increase is partially offset by an assumption of a corresponding reduction in the saturation level during filling (as discussed further in 3.3.2.2).

The emissions estimated by equation 14 were confirmed to exceed the stated lower bound of standing idle emissions in the absence of wind effects (per equation 5). This check was performed, however, with the assumption of a white tank with the paint in good condition. It has subsequently been observed that tank colors other than white will result in higher standing idle losses for an internal floating-roof tank than for an external floating-roof tank. Again, however, without data to guide an improvement in the approach used to model the wind-driven losses, there is no foundation upon which to base a change in the calculation.

3.2.3 Internal or External Floating-Roof Tanks That Drain Dry.

Standing idle losses from either an internal or an external floating-roof tank that has been drained dry are modeled as the evaporation of a thin layer of liquid clinging to the bottom of the tank. The absence of a liquid heel implies that the tank bottom is designed to allow withdrawal of virtually all free flowing liquid (i.e., drain-dry tanks). When a drain-dry tank has been completely emptied, the only stock liquid available to evaporate is that remaining on wetted surfaces of the tank interior. This evaporation of liquid clinging to a surface is termed *clingage loss*.

The 1998-1999 field testing demonstrated that the limited quantity of stock liquid that remains in drain-dry tanks is insufficient to sustain daily replenishment of stock vapors under the floating roof. This has already been observed in Figure 7, where stock vapors do not return after the wind has flushed out those stock vapors that were generated initially. Figure 8 presents the trends in nominal saturation level for all four test tanks, where it is apparent that the two drain-dry tanks (Test Tanks 1 and 4) do not sustain their initial level of saturation, whereas the saturation level does remain fairly constant in the tanks with a liquid heel (Test Tanks 2 and 3). It appears, then, that neither of the daily standing idle loss mechanisms (i.e., thermal breathing and wind effects) would apply to a drain-dry tank. The standing idle loss mechanism for drain-dry tanks is the evaporation of the thin layer of liquid clinging to the bottom of the tank. This would be a one-time event, rather than a daily event, and thus the estimate of standing idle loss for a drain-dry tank is independent of the number of days that the tank stands idle.

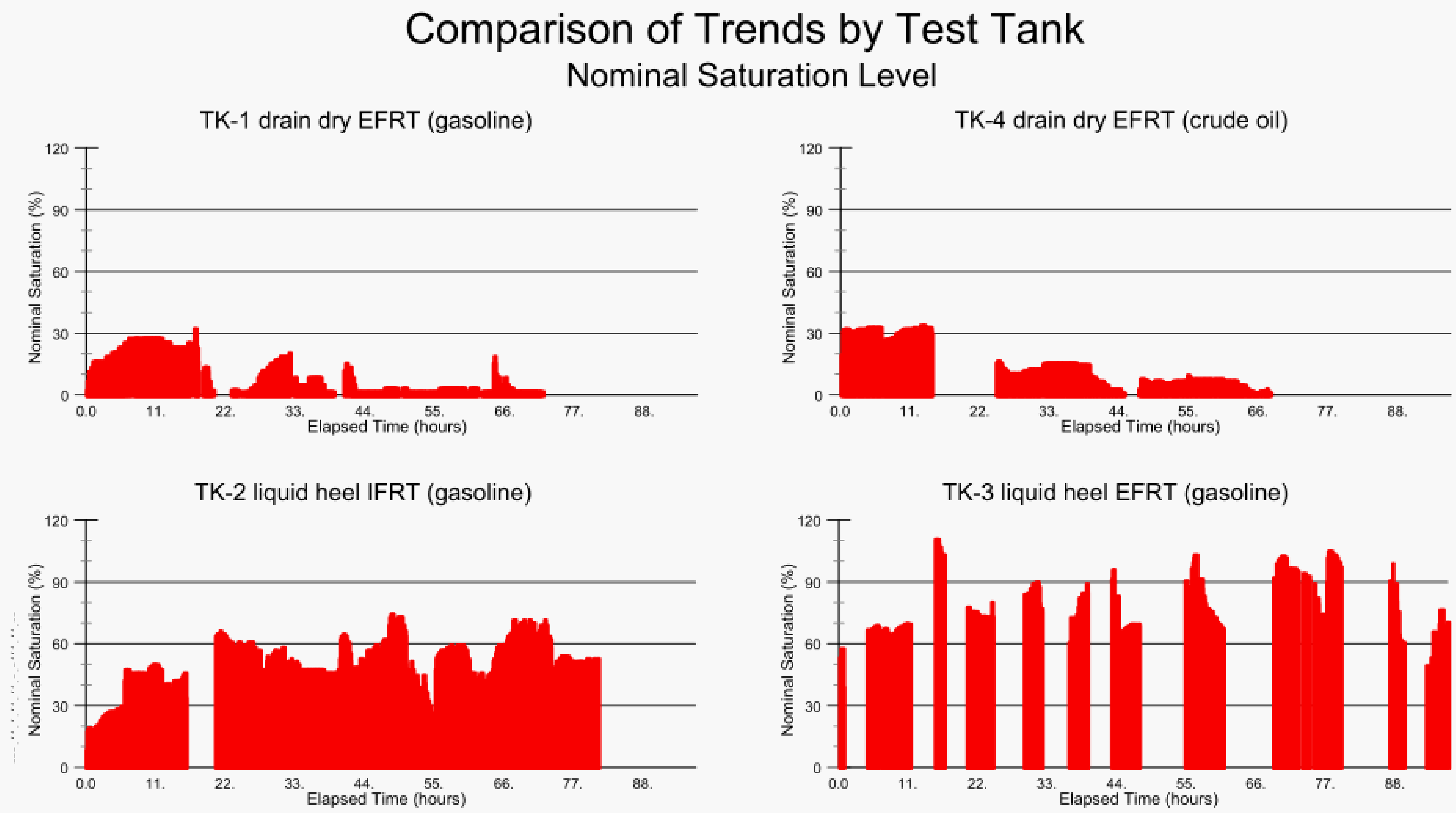


Figure 8. Saturation Pattern of Drain-Dry Tanks versus Tanks with a Liquid Heel.

3.2.3.1 Confidence in the Clingage Model. The equation used in this model calculates the weight of an assumed thickness of stock liquid film clinging to the bottom of the tank, and should be a reliable predictor of clingage loss when the variables are evaluated correctly. The critical required input, then, is the assumed thickness of liquid film. This variable is identified as the clingage factor, C.

While standing idle losses from a drain-dry tank appear to be limited to evaporation of bottom clingage, the thickness of the layer that evaporates is not known. In the absence of data, a value was selected to generate an estimate of landing losses for drain-dry tanks that does not exceed the landing loss for an IFRT with a liquid heel, even if the IFRT with a liquid heel were to stand idle for only one day. The clingage factor chosen corresponds to a liquid layer thickness of approximately 0.01 inches.

3.2.3.2 Derivation of the Clingage Model. The 10/1/97 TGB report [15] had dismissed clingage loss as negligible, based on the factors typically used for evaporation from a wetted tank shell. The vapor concentrations measured for Test Tanks 1 and 4, however, indicate that a greater amount of stock liquid is evaporating than would be assumed to cling to a vertical tank shell. This is not surprising, considering that even these sloped tank bottoms are much nearer to horizontal than vertical. Furthermore, tank bottoms tend to have at least a thin layer of sludge which can trap small amounts of liquid, whereas the tank shell is continually wiped clean by the rim seal. This drain-dry standing idle loss mechanism, then, requires a larger clingage factor than that used for a clean tank shell.

Clingage factors are published in Table 17 of API MPMS 19.2. The conditions listed are light rust (typically assumed for tank shells in normal repair, without internal linings), dense rust, and gunite-lined. Of these, the one that best approximates the condition of the sludge-lined tank bottom is gunite-lined.

The clingage factor, C, is given in terms of barrels per thousand square feet. It is converted to units of gallons per square foot as follows:

$$Clingage\left(\frac{\text{gallons}}{\text{ft}^2}\right) = C\left(\frac{\text{bbl}}{1000\,\text{ft}^2}\right) \times 42\left(\frac{\text{gallons}}{\text{bbl}}\right) = 0.042\,C \qquad (15)$$

To convert from gallons to pounds, multiply by the liquid density, W_l, in pounds per gallon.

$$Clingage\left(\frac{\text{pounds}}{\text{ft}^2}\right) = 0.042\,C \times W_l \qquad (16)$$

The total clingage loss in pounds, L_c, for a given area is then:

$$L_c = 0.042\,C\,W_l\,(Area) \qquad (17)$$

The area to be included is that of the bottom of the tank, in units of square feet. Clingage to the tank shell under the floating roof and to the underside of the floating roof itself would still be considered negligible.

Applying this approach to various scenarios revealed that, in certain cases, it caused the estimated landing loss for a drain-dry tank to significantly exceed the estimated landing loss for a tank with a liquid heel. This was corrected by using the clingage factor of 0.15 for crude oil as well as for refined stocks, and establishing an upper bound for clingage loss equal to the filling loss for an internal floating-roof tank with a liquid heel (see 3.3 and 3.3.1). The resulting standing idle loss equation for a drain-dry tank is expressed as follows:

$$L_S = 0.0063\,W_l\left(\pi\,D^2/4\right) \le \left(\frac{P\,V_V}{R\,T}\right)M_V\,S \qquad (18)$$

3.3 Filling Loss Mechanism

Filling loss is the loss associated with refilling the tank to a level sufficient to float the floating roof. The loss mechanism is the displacement of vapors from beneath the floating roof by the incoming liquid. The volume of vapors displaced is readily determined from the diameter of the tank and the height of the floating roof above either the tank floor or the liquid heel. The amount of stock vapors included in that volume is then determined from the concentration of stock vapors in the vapor space, which was presented in Section 2 as a function of the saturation factor, *S*. API MPMS 19.1 presents the filling loss in terms of annual throughput. The 10/1/97 report showed the conversion of this equation to filling loss per episode, in terms of the volume of the vapor space. The filling loss may be expressed as follows:

$$L_F = 0.000178\,(P\,V_V)\,M_V\,S \qquad (19)$$

Recognizing that the constant, 0.000178 represents the term $1/(RT)$, based on a typical value of 63°F (523°R) for *T*, the filling loss equation may be restated as the pounds of stock vapor in the vapor space, $[(PV_V)/(RT)]M_V$, times the saturation factor, *S*.

$$L_F = \left(\frac{P\,V_V}{R\,T}\right) M_V\;S \qquad (20)$$

There are two sources contributing to the presence of stock vapors during filling. The first source is evaporation of stock liquid remaining in the bottom of the tank while it is standing idle, as discussed in 3.2. This is referred to as the *arrival* component. The arrival component was the subject of the field testing conducted under Part II of this study. As discussed in 3.2.2, wind action may reduce or eliminate the arrival component of stock vapors in the case of an external floating-roof tank with a liquid heel. The lack of sufficient stock liquid to sustain continued evaporation may result in elimination of the arrival component of stock vapors in a drain-dry tank, as discussed in 3.2.3.

The other source of stock vapors during filling is evaporation of the incoming stock liquid, referred to as the *generated* component. The generated component will result in loss of stock vapors even when loading a tank after it has been degassed and cleaned.

3.3.1 Internal Floating-Roof Tanks with a Liquid Heel.

An internal floating roof tank with a liquid heel would not be subject to either of the modifying circumstances discussed above (i.e., drain-dry tank operations or wind effects). It would therefore be expected that the filling, or loading, situation would be similar to that for other vessels and tanks.

3.3.1.1 Confidence in the Submerged-Fill Loading Model. The equation for loading or filling losses is derived from the ideal gas laws, and should be a reliable predictor of filling loss when the variables are evaluated correctly. The critical required input is the saturation factor, *S*.

There is an accepted value, published in EPA's *AP-42* document,[5] for the saturation factor when loading petroleum liquids into a vessel in a submerged fill manner. On the basis of the EPA factors, a value of 0.6 was proposed in the 1/23/02 TGB report, for tanks with a full liquid heel. This value was spot validated by the 2003 field testing program. A slightly lower value (0.5) for tanks with a partial liquid heel was supported by the field studies of 2003 and 2004.

3.3.1.2 Derivation of the Submerged-Fill Loading Model. Saturation factors for various loading conditions are given in Table 5.2-1 of EPA's *AP-42* document. The lowest factor given for loading into a tank or vessel already containing stock liquid is 0.6, for the condition of loading through a submerged fill line.

As discussed in the 10/1/97 TGB report, the saturation factor may also be assessed by examining the factor for breathing loss in accordance with API MPMS 19.1. When evaluating breathing loss saturation for gasoline as the stock liquid and a vapor space height typical of landed floating roofs, the saturation factor for the arrival component tends to be somewhat less than 0.6. The AP-42 factor of 0.6 would then seem to reasonably allow for additional stock vapors from the generated component during loading.

3.3.2 External Floating-Roof Tanks with a Liquid Heel.

The flushing of vapors from beneath a landed external floating roof by wind essentially degasses the vapor space. When the tank has a heel of stock liquid remaining in the bottom, however, the stock vapors are being continually replenished. The stock vapor concentration at filling would therefore be expected to be less than for the internal floating roof with a liquid heel, but more than for the drain-dry tank.

3.3.2.1 Confidence in the Wind-Affected Loading Model. The equation for loading or filling losses is derived from the ideal gas laws, and should be a reliable predictor of filling loss when the variables are evaluated correctly. The critical required input is the saturation factor, S, as modified by the coefficient, C_{sf}.

Accepted published values for saturation factors when loading petroleum liquids do not address the scenario of partial evacuation of the arrival component by wind action. The proposed method maintains the saturation factor between rational upper and lower bounds. The upper bound is the saturation factor for submerged fill loading with no wind action (i.e., full arrival component of vapors) and the lower bound is for loading into a degassed vessel (i.e., no arrival component of vapors). While this method of determining an intermediate level for the arrival component of vapors is arbitrarily determined, the actual value would be expected to range between the identified bounds in a manner similar to that assumed.

3.3.2.2 Derivation of the Wind-Affected Loading Model. The TGB interim report of December 23, 1998, presented a coefficient, C_{sf}, for reducing the filling loss saturation factor as a function of the increase in standing idle loss attributed to wind effects, such that:

$$L_F = \left(\frac{P\,V_V}{R\,T}\right) M_V \left(C_{sf}\ S\right) \qquad (21)$$

where:

$$C_{sf} = 1 - \frac{(one\text{-}day\ wind\text{-}driven\ Stnding\ Idle\ Loss) - (one\text{-}day\ without\ wind\ Stnding\ Idle\ Loss)}{(one\text{-}day\ without\ wind\ Total\ Loss)} \qquad (22)$$

The underlying premise is that vapors expelled by wind action will no longer be present in the vapor space when the tank is refilled, and therefore may be deducted from the filling loss saturation factor S for the case of no wind action. Substituting the equations developed previously for each of the terms in equation 22 allows this expression to be written in the following form:

$$C_{sf} = 1 - \frac{(equation\ 14) - (equation\ 5)}{(equation\ 5) + (equation\ 20)} \qquad (23)$$

where the number of days, n_d, in equations 5 and 14 are assigned a value of 1.

The TGB interim report evaluated this approach with regard to the identified upper and lower bounds. The formulation of equation 23 insures that the value of C_{sf} rarely exceeds 1.0, thereby complying with the upper bound requirement that the filling loss saturation factor after adjusting for wind effects shall not exceed that when no wind action is present.

The lower bound scenario occurs when wind virtually eliminates stock vapors from beneath the floating roof. This would be similar to the situation for a drain-dry tank, where only the generated component of stock vapors need be considered for filling loss. The filling loss saturation factor for this situation is determined in 3.3.3.2 to be 0.15, and thus:

$$C_{sf}\, S \geq 0.15 \tag{24}$$

With this lower bound, the model satisfies the identified boundary considerations.

3.3.3 Internal or External Floating-Roof Tanks That Drain Dry.

As discussed in 3.2.3, drain-dry tanks experience an initial evaporation of stock liquid clinging to the tank bottom, but the remaining sludge does not continue to produce stock vapors at a measurable level. In that the arrival component of stock vapors is entirely accounted for as clingage loss, only the generated component need be considered for the filling loss.

3.3.3.1 Confidence in the Drain-Dry Loading Model. The equation for loading or filling losses is derived from the ideal gas laws, and should be a reliable predictor of filling loss when the variables are evaluated correctly. The critical required input is the saturation factor, *S*.

There is an accepted published value for the saturation factor when loading petroleum liquids into a vessel that has previously been degassed. Deviation from this accepted value would only be warranted if sufficient data were available to justify a different value.

3.3.3.2 Derivation of the Drain-Dry Loading Model. API Publication 2514A, *Atmospheric Hydrocarbon Emissions from Marine Vessel Transfer Operations*,[6] provides emission factors for the loading of gasoline and crude oil into compartments as a function of the prior state of the compartment. The drain-dry tank would constitute a similar condition to the case of loading into a compartment that had been previously cleaned, in that there is no arrival component of stock vapors. The associated emission factor may be converted to a saturation factor, as shown in the 10/1/97 TGB report. The equivalent saturation factor for this case is approximately 0.15, for both gasoline and crude oil.

4. SAMPLE CALCULATIONS

4.1 Accounting for Cone-Down Bottoms

As illustrated in Figure 9, the height of the vapor space, h_v, in the presence of a liquid heel may be expressed as follows:

$$h_v = h_d - h_l \tag{25}$$

where:

h_d = the height of the deck above the tank bottom at the tank shell, in feet, and

h_l = the height of the liquid above the tank bottom at the tank shell, in feet.

If the tank has a flat bottom, then the effective height of the stock liquid, h_{le}, is the same as the height of the liquid above the tank bottom at the tank shell (i.e., $h_{le} = h_l$).

When there is a significant slope to the tank bottom, however, these relationships require some modification. In the case of a cone-down bottom, there is additional enclosed volume below the level of the bottom of the tank shell, as illustrated in Figure 10.

Figure 9. Volume of Vapor Above a Liquid Heel

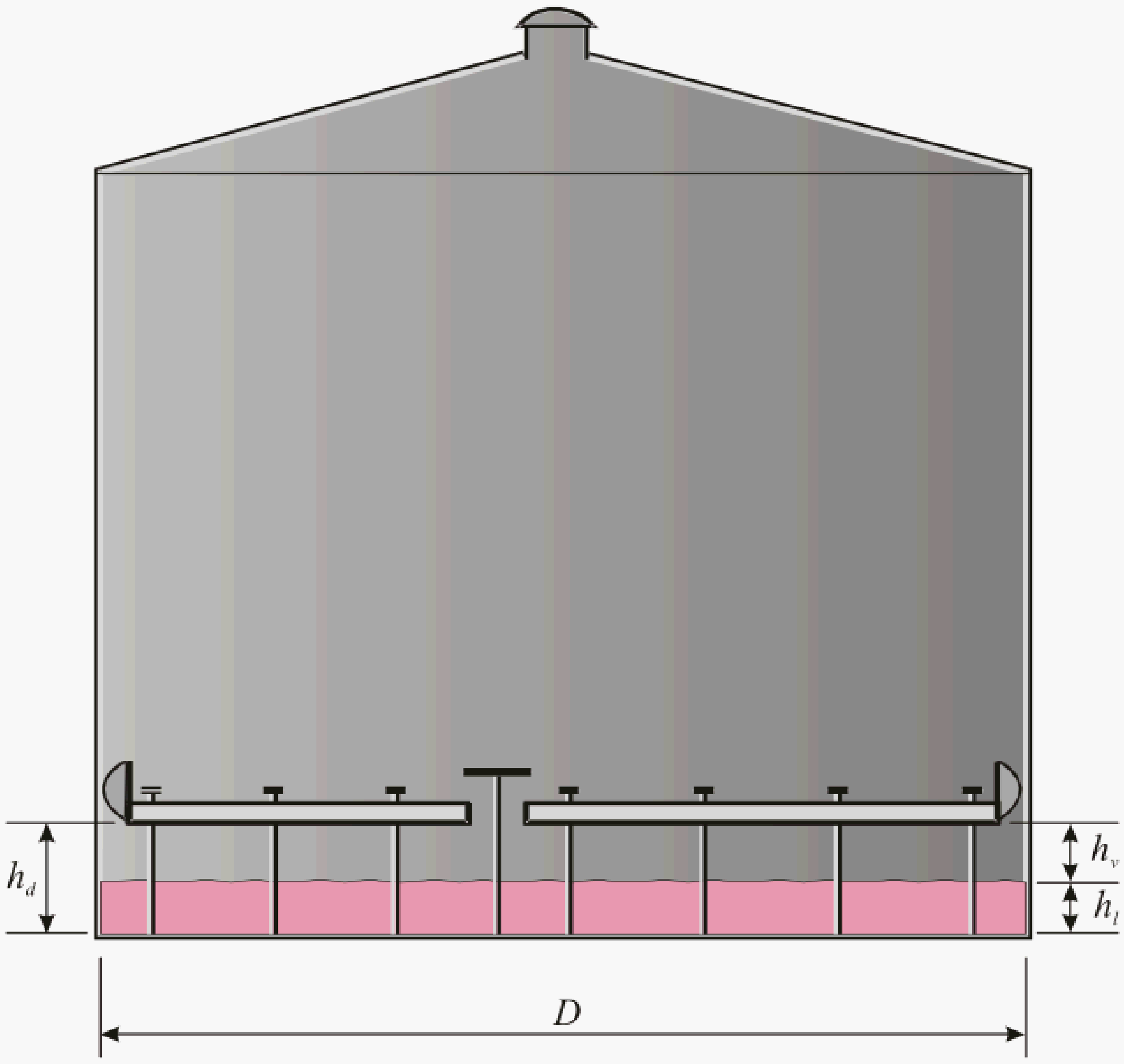
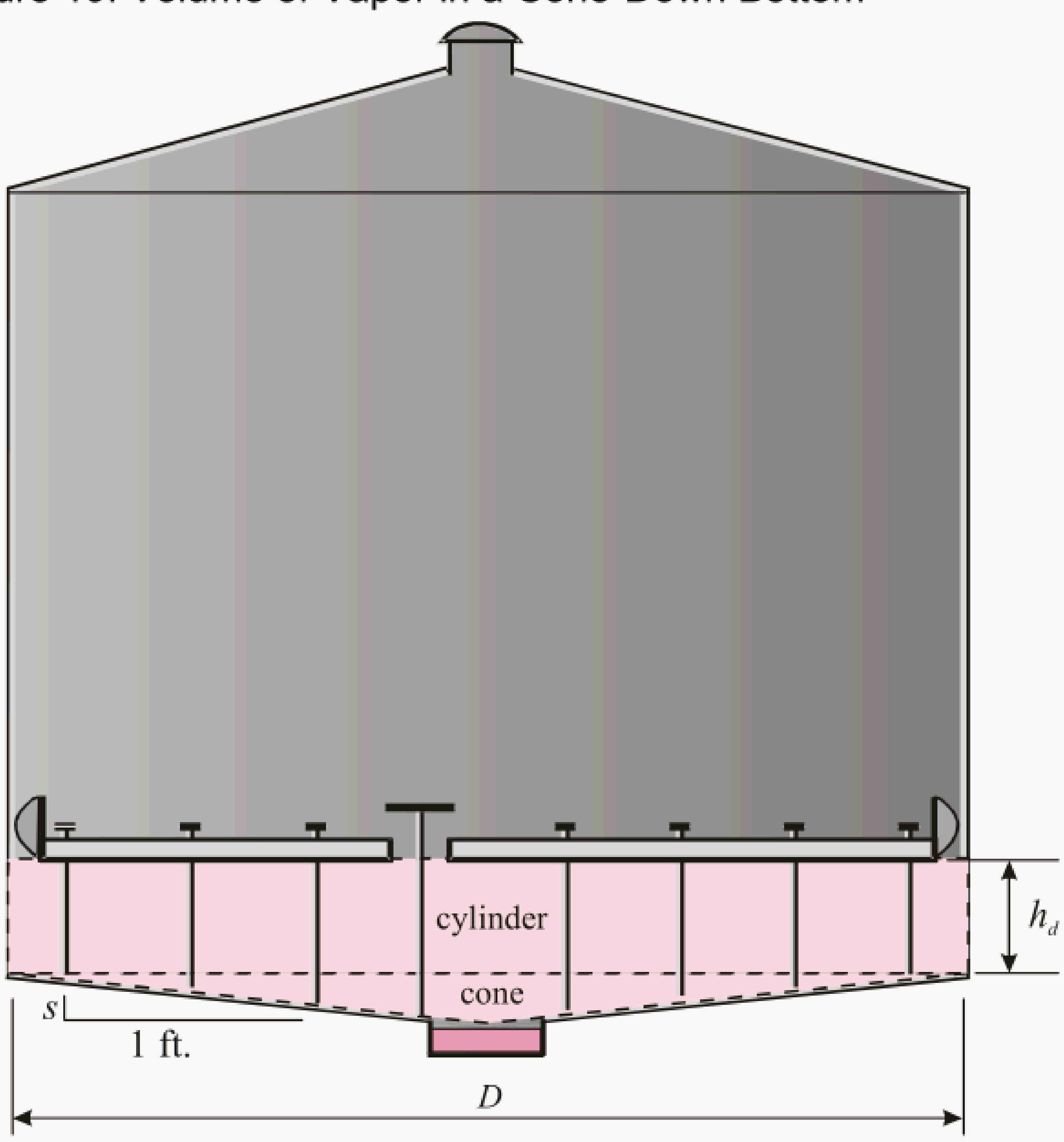


Figure 10. Volume of Vapor in a Cone-Down Bottom



The average height of a cone may be expressed as:

$$\text{avg. ht. of cone} = \frac{sD}{72} \qquad (26)$$

where:

s = slope, in inches per foot, and

D = the tank diameter, in feet.

The constant, 72, has units of inches per foot.

The average height of the space under the deck is therefore equal to:

$$\left[h_d + \frac{sD}{72}\right] \qquad (27)$$

The average, or effective, height of a liquid heel (if present) would be:

$$h_{le} = \left[h_l + \frac{sD}{72}\right] \qquad (28)$$

The height of the vapor space for a tank with a cone-down bottom may be expressed as:

$$h_v = \left(h_d + \frac{sD}{72}\right) - h_{le} \qquad (29)$$

Equations 28 and 29 may be reduced to the expressions shown in Table 3, for the specific conditions indicated.

Table 3. Effective Height of Liquid, h_{le}, and Height of Vapor Space, h_v

	Liquid Heel		Drain Dry	
Bottom configuration	Flat ($s = 0$)	Cone-down	Flat ($s = 0$)	Cone-down
Effective height of liquid, h_{le}	h_l	$h_l + (sD / 72)$	0	0
Height of vapor space, h_v	$h_d - h_l$	$h_d - h_l$	h_d	$h_d + (sD / 72)$

Another condition to consider in the configuration of the tank bottom is the presence of a sump. The volume of a bottom sump can generally be neglected in the estimation of the height of the vapor space, h_v. If the only free-standing liquid in the tank is that which is in the sump, however, then the volume of liquid in the sump should be accounted for in the determination of the effective height of liquid, h_{le}.

The effective height of the liquid is used in equation 10 to determine an upper limit on standing-idle loss for tanks with a liquid heel. This term is called the effective height, because it refers to the height of liquid that would result if all of the available stock liquid were distributed evenly over the horizontal area of the tank bottom. If there is liquid in the sump, the volume of that liquid should be calculated, and then divided by the horizontal cross-sectional area of the tank in order to determine an effective height for the stock liquid.

4.2 Worked Examples

The floating-roof landing losses estimated by this model are presented in Appendix I for the following examples. These examples assume a flat-bottom tank.

Example 1: Gasoline, seven-foot leg height.

Example 2: Gasoline, three-foot leg height.

Example 3: Gasoline, three-foot leg height (large diameter, light gray tank, high temperature).

Example 4: Crude Oil, six-foot leg height.

Example 5: Diesel, three-foot leg height.

The calculation procedure proposed in this report directly estimates filling losses, without differentiating between the arrival and generated components discussed in 3.3. The summary of losses shown for each example, however, does separate the filling loss into the arrival and generated components, with the associated levels of saturation designated as (S_a) and (S_g), respectively. This separation into arrival and generated components is done strictly for illustrative purposes in these examples. The level of saturation resulting from the generated component (S_g) is set equal to 0.15, with a couple of limiting conditions. The first limiting condition is that the total level of saturation (S) for the filling loss shall be not greater than 0.6 for a full liquid heel or 0.5 for a partial liquid heel. The second limiting condition is that the saturation level associated with the arrival component (S_a) must be greater than or equal to the breathing loss saturation factor (K_s). These conditions are embedded into the proposed calculation procedure for the filling loss, without requiring separate calculation steps for the arrival and generated components.

5. CONCLUSION

Floating-roof landing losses may be estimated as a two-step procedure. The first step is to estimate the standing idle loss, and the second step is to estimate the filling loss.

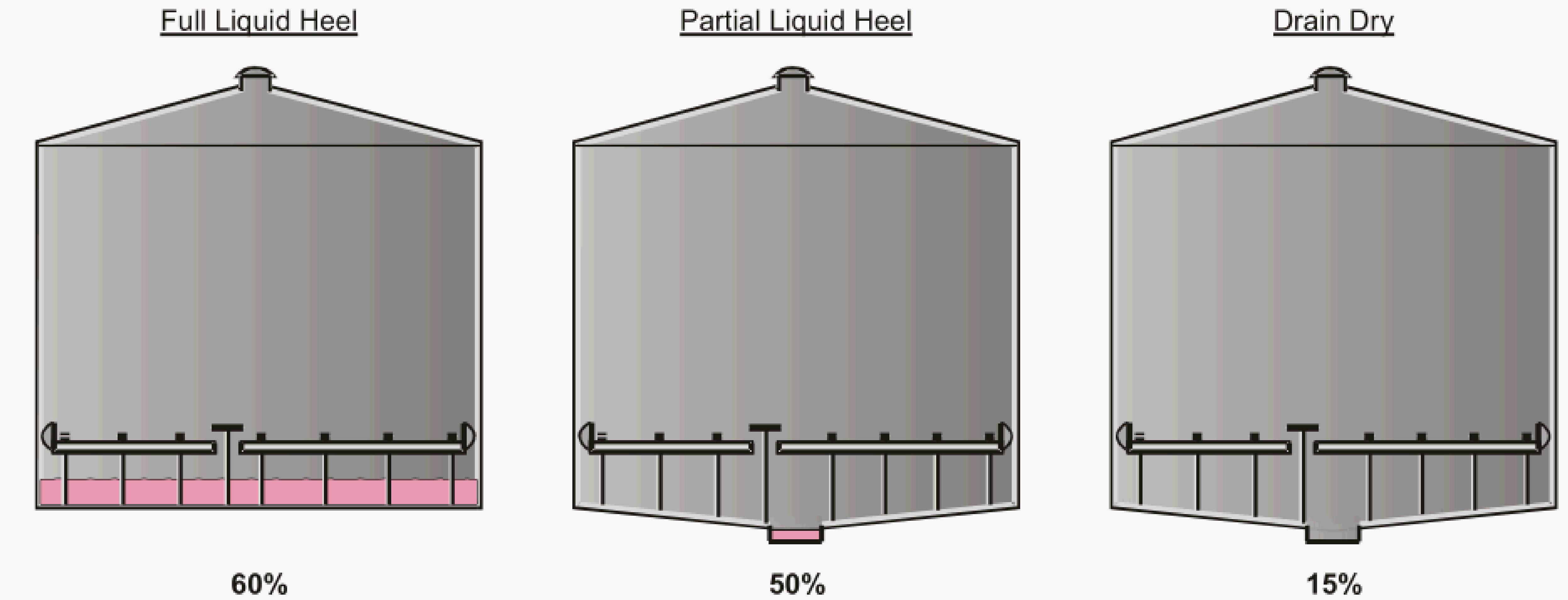
The standing idle loss is calculated as follows:

IFRT with a full or partial liquid heel .... as breathing loss, similar to a fixed-roof tank.

EFRT with a full or partial liquid heel .... as wind-driven loss, similar to rim-seal loss.

IFRTs and EFRTs that drain dry .... as a heavy clingage loss.

The filling loss is calculated as the volume of the vapor space under the floating roof, times the concentration of vapors in that space. The vapor concentration is a function of the saturation level of the vapors. For internal floating-roof tanks, the saturation factors are as follows:



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For external floating-roof tanks, a somewhat lower saturation factor is calculated for the filling loss, due to wind effects.

The calculation steps for each scenario are summarized in Table 1, which is repeated on the next page. The emissions calculated in accordance with this model are for a single landing episode. The annual emissions resulting from floating roof landings would be the sum of the emissions for each of the individual episodes.

Table 1. Summary of Floating-Roof Landing Loss Estimation Methods by Tank Type (per Episode)

	Internal Floating-Roof Tanks with a Liquid Heel	External Floating-Roof Tanks with a Liquid Heel	all Drain-Dry Tanks
Standing Idle Loss	(daily)	(daily)	(one-time event)
Equation	equations 5 & 10	equations 14 & 10	equation 18
	$L_S = n_d\ K_E \left(\frac{P\ V_V}{R\ T}\right) M_V\ K_S$	$L_S = 0.57\ n_d\ \ D\ P^*\ M_V$	$L_S = 0.0063\ W_l\ \left(\pi\ D^2/4\right)$
	but $\leq 5.9\ D^2\ h_{le}\ W_l$	but $\leq 5.9\ D^2\ h_{le}\ W_l$	but $\leq \left(P\ V_V / R\ T\right) M_V\ \ S$ using the IFRT value for S
Standing Idle Saturation Factor, K_S	K_S from equation 8. not to exceed S for filling.	not applicable	not applicable
Filling Loss	equation 20	equation 21	equation 20
Equation	$L_F = \left(\frac{P\ V_V}{R\ T}\right) M_V\ \ S$	$L_F = \left(\frac{P\ V_V}{R\ T}\right) M_V\ \left(C_{sf}\ \ S\right)$	$L_F = \left(\frac{P\ V_V}{R\ T}\right) M_V\ \ S$
Filling Saturation Factor, S	$S = 0.60$ for a full heel $S = 0.50$ for a partial heel	but $C_{sf}\, S \geq 0.15$ using the IFRT value for S and C_{sf} is from equation 23.	$S = 0.15$

Limitations to the proper use of these calculations

- Tank Degassing and Cleaning. These calculations do not address emissions from activities such as degassing or tank cleaning. Such emissions would be in addition to the standing idle and refilling emissions estimated by these calculations.
- Product Factors. The model is intended for use with any petroleum liquid. The inclusion in the model of the stock liquid's physical properties (i.e., true vapor pressure, vapor molecular weight, and liquid density) appears to effectively differentiate crude oil from gasoline, and therefore no further differentiation should be made in the form of product factors or other product-specific adjustments.
- Change of Service. The model assumes that the stock liquid used to refill the tank is the same as that stored prior to landing the floating roof. Situations in which there is a change of service (i.e., the tank is to be filled with a different stock than it had been storing) may warrant differentiating between the stock vapor properties for the arrival and generated components of filling loss.
- Partial Days. The model does not address standing idle losses for partial days. It would be conservative (i.e., potentially overestimate emissions) to apply the model to episodes during which the floating roof remains landed for less than a day.

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APPENDIX I—EXAMPLES

Example 1: Gasoline, seven-foot leg height.

Example 2: Gasoline, three-foot leg height.

Example 3: Gasoline, three-foot leg height (large diameter, light gray tank, high temperature).

Example 4: Crude Oil, six-foot leg height.

Example 5: Diesel, three-foot leg height.

Example 1: Gasoline, seven-foot leg height.

Stored liquid:	**Gasoline**			Liquid Temp		Liquid Density	Atmos Pressure			Ideal Gas Constant
	distillation	Antoine's Constants								
RVP	slope	A	B	Tla	TVP	Wl	Pa	P*	Mv	R
10	**3.0**	11.724	5,237.3	**60**	5.22	**6.1**	**14.7**	0.1092	**66**	10.731
				(deg F)	(psia)	(lb/gallon)	(psia)		(lb/lb-mole)	(psia ft^3) / (lb-mole R)

Tank Diameter **100** feet

height of deck above the bottom of the tank shell
(leg height setting) **7** feet
height of liquid (for cases with a liquid heel)
1 feet

Determination of vapor space expansion factor:

delta(Pb) =	**0**	assumes freely vented vapor space
I =	**1370**	average value for continental US
alpha =	**0.17**	tank paint: **white, good condition**
delta(Ta) =	**20**	average value for continental US
delta(Tv) =	20.9	calculated from above
Ke =	0.152	vapor space expansion factor (calculated)

Loss (pounds per event)

Equation		Days Idle Prior to Refill: 1	2	3		
	IFRT with full liquid heel	cumulative standing-idle loss				
5	**Standing Idle (breathing):**	**166**	**332**	**498**	**Ks = 0.38**	equation 8.
	resident vapors under the deck:	1,309	1,309	1,309	Sa = 0.45	arrival component of filling loss.
	add'l generated during filling:	436	436	436	Sg = 0.15	generated component of filling loss.
20	(count only on day of refill) **Filling:**	**1,745**	**1,745**	**1,745**	**total S = 0.60**	
	Total:	1,911	2,077	2,243		
	IFRT with partial liquid heel	cumulative standing-idle loss				
5	**Standing Idle (breathing):**	**166**	**332**	**498**	**Ks = 0.38**	equation 8.
	resident vapors under the deck:	1,094	1,094	1,094	Sa = 0.38	arrival component of filling loss.
	add'l generated during filling:	361	361	361	Sg = 0.12	generated component of filling loss.
20	(count only on day of refill) **Filling:**	**1,454**	**1,454**	**1,454**	**total S = 0.50**	
	Total:	1,620	1,786	1,952		
	EFRT with full liquid heel	cumulative standing-idle loss				
14	**Standing Idle (wind driven):**	**411**	**822**	**1,232**		
	resident vapors under the deck:	1,085	1,085	1,085	Sa = 0.37	arrival component of filling loss.
	add'l generated during filling:	436	436	436	Sg = 0.15	generated component of filling loss.
21	(count only on day of refill) **Filling:**	**1,522**	**1,522**	**1,522**	**total (Csf S) = 0.52**	equation 24;
	Total:	1,933	2,343	2,754		where Csf is from equation 23 and S = 0.6
	EFRT with partial liquid heel	cumulative standing-idle loss				
14	**Standing Idle (wind driven):**	**411**	**822**	**1,232**		
	resident vapors under the deck:	798	798	798	Sa = 0.27	arrival component of filling loss.
	add'l generated during filling:	436	436	436	Sg = 0.15	generated component of filling loss.
21	(count only on day of refill) **Filling:**	**1,235**	**1,235**	**1,235**	**total (Csf S) = 0.42**	equation 24;
	Total:	1,646	2,056	2,467		where Csf is from equation 23 and S = 0.5
	IFRT or EFRT, drain dry	cumulative standing-idle loss (no add'l standing idle loss after the first day)				
18	**Standing Idle (clingage):**	**302**	**302**	**302**		
	resident vapors under the deck:	302	302	302		arrival component incl. w/Standing Idle.
	add'l generated during filling:	509	509	509	S = 0.15	generated component of filling loss.
20	(count only on day of refill) **Filling:**	**509**	**509**	**509**	**total S = 0.15**	
	Total:	811	811	811		

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Example 2: Gasoline, three-foot leg height.

Stored liquid: **Gasoline**				Liquid		Liquid	Atmos			Ideal Gas
	distillation	Antoine's Constants		Temp		Density	Pressure			Constant
RVP	slope	A	B	Tla	TVP	Wl	Pa	P*	Mv	R
10	**3.0**	11.724	5,237.3	**60**	5.22	**6.1**	**14.7**	0.1092	**66**	10.731
				(deg F)	(psia)	(lb/gallon)	(psia)		(lb/lb-mole)	(psia ft^3) (lb-mole R)

Tank Diameter **100** feet

height of deck above the bottom of the tank shell
(leg height setting) **3** feet

height of liquid (for cases with a liquid heel)
1 feet

Determination of vapor space expansion factor:

delta(Pb) =	**0**	assumes freely vented vapor space
I =	**1370**	average value for continental US
alpha =	**0.17**	tank paint: **white, good condition**
delta(Ta) =	**20**	average value for continental US
delta(Tv) =	20.9	calculated from above
Ke =	0.152	vapor space expansion factor (calculated)

Loss (pounds per event)

Equation		Days Idle Prior to Refill: 1	2	3		
	IFRT with full liquid heel	cumulative standing-idle loss				
5	**Standing Idle (breathing):**	**88**	**177**	**265**	**Ks = 0.60**	equation 8.
	resident vapors under the deck:	582	582	582	Sa = 0.60	arrival component of filling loss.
	add'l generated during filling:	0	0	0	Sg = 0.00	generated component of filling loss.
20	(count only on day of refill) **Filling:**	**582**	**582**	**582**	**total S = 0.60**	
	Total:	670	758	847		
	IFRT with partial liquid heel	cumulative standing-idle loss				
5	**Standing Idle (breathing):**	**74**	**147**	**221**	**Ks = 0.50**	equation 8.
	resident vapors under the deck:	485	485	485	Sa = 0.50	arrival component of filling loss.
	add'l generated during filling:	0	0	0	Sg = 0.00	generated component of filling loss.
20	(count only on day of refill) **Filling:**	**485**	**485**	**485**	**total S = 0.50**	
	Total:	558	632	706		
	EFRT with full liquid heel	cumulative standing-idle loss				
14	**Standing Idle (wind driven):**	**411**	**822**	**1,232**		
	resident vapors under the deck:	156	156	156	Sa = 0.16	arrival component of filling loss.
	add'l generated during filling:	145	145	145	Sg = 0.15	generated component of filling loss.
21	(count only on day of refill) **Filling:**	**302**	**302**	**302**	**total (Csf S) = 0.31**	equation 24;
	Total:	713	1,123	1,534		where Csf is from equation 23 and S = 0.6
	EFRT with partial liquid heel	cumulative standing-idle loss				
14	**Standing Idle (wind driven):**	**411**	**822**	**1,232**		
	resident vapors under the deck:	47	47	47	Sa = 0.05	arrival component of filling loss.
	add'l generated during filling:	145	145	145	Sg = 0.15	generated component of filling loss.
21	(count only on day of refill) **Filling:**	**192**	**192**	**192**	**total (Csf S) = 0.20**	equation 24;
	Total:	603	1,014	1,424		where Csf is from equation 23 and S = 0.5
	IFRT or EFRT, drain dry	cumulative standing-idle loss (no add'l standing idle loss after the first day)				
18	**Standing Idle (clingage):**	**302**	**302**	**302**		
	resident vapors under the deck:	302	302	302		arrival component incl. w/Standing Idle.
	add'l generated during filling:	218	218	218	S = 0.15	generated component of filling loss.
20	(count only on day of refill) **Filling:**	**218**	**218**	**218**	**total S = 0.15**	
	Total:	520	520	520		

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Example 3: Gasoline, three-foot leg height - Large diameter, light gray tank; high temperature.

Stored liquid: **Gasoline**				Liquid		Liquid	Atmos			Ideal Gas
	distillation	Antoine's Constants		Temp		Density	Pressure			Constant
RVP	slope	A	B	Tla	TVP	Wl	Pa	P*	Mv	R
10	**3.0**	11.724	5,237.3	**80**	7.58	**6.1**	**14.7**	0.1792	**66**	10.731
				(deg F)	(psia)	(lb/gallon)	(psia)		(lb/lb-mole)	(psia ft^3) / (lb-mole R)

Tank Diameter **200** feet

height of deck above the bottom of the tank shell
(leg height setting) **3** feet
height of liquid (for cases with a liquid heel)
1 feet

Determination of vapor space expansion factor:

delta(Pb) =	**0**	assumes freely vented vapor space
I =	**1800**	**above average**
alpha =	**0.54**	tank paint: **light gray, good condition**
delta(Ta) =	**20**	average value for continental US
delta(Tv) =	41.6	calculated from above
Ke =	0.475	vapor space expansion factor (calculated)

Loss (pounds per event) — Days Idle Prior to Refill

Equation		1	2	3		
	IFRT with full liquid heel	cumulative standing-idle loss				
5	**Standing Idle (breathing):**	**1,428**	**2,856**	**4,284**	**Ks = 0.55**	equation 8.
	resident vapors under the deck:	3,007	3,007	3,007	Sa = 0.55	arrival component of filling loss.
	add'l generated during filling:	247	247	247	Sg = 0.05	generated component of filling loss.
20	(count only on day of refill) **Filling:**	**3,254**	**3,254**	**3,254**	**total S = 0.60**	
	Total:	4,682	6,110	7,538		
	IFRT with partial liquid heel	cumulative standing-idle loss				
5	**Standing Idle (breathing):**	**1,287**	**2,575**	**3,862**	**Ks = 0.50**	equation 8.
	resident vapors under the deck:	2,712	2,712	2,712	Sa = 0.50	arrival component of filling loss.
	add'l generated during filling:	0	0	0	Sg = 0.00	generated component of filling loss.
20	(count only on day of refill) **Filling:**	**2,712**	**2,712**	**2,712**	**total S = 0.50**	
	Total:	3,999	5,287	6,574		
	EFRT with full liquid heel	cumulative standing-idle loss				
14	**Standing Idle (wind driven):**	**1,349**	**2,697**	**4,046**		
	resident vapors under the deck:	2,496	2,496	2,496	Sa = 0.46	arrival component of filling loss.
	add'l generated during filling:	814	814	814	Sg = 0.15	generated component of filling loss.
21	(count only on day of refill) **Filling:**	**3,309**	**3,309**	**3,309**	**total (Csf S) = 0.61**	equation 24;
	Total:	4,658	6,006	7,355		where Csf is from equation 23 and S = 0.6
	EFRT with partial liquid heel	cumulative standing-idle loss				
14	**Standing Idle (wind driven):**	**1,349**	**2,697**	**4,046**		
	resident vapors under the deck:	1,857	1,857	1,857	Sa = 0.34	arrival component of filling loss.
	add'l generated during filling:	814	814	814	Sg = 0.15	generated component of filling loss.
21	(count only on day of refill) **Filling:**	**2,670**	**2,670**	**2,670**	**total (Csf S) = 0.49**	equation 24;
	Total:	4,019	5,367	6,716		where Csf is from equation 23 and S = 0.5
	IFRT or EFRT, drain dry	cumulative standing-idle loss (no add'l standing idle loss after the first day)				
18	**Standing Idle (clingage):**	**1,207**	**1,207**	**1,207**		
	resident vapors under the deck:	1,207	1,207	1,207		arrival component incl. w/Standing Idle.
	add'l generated during filling:	1,220	1,220	1,220	S = 0.15	generated component of filling loss.
20	(count only on day of refill) **Filling:**	**1,220**	**1,220**	**1,220**	**total S = 0.15**	
	Total:	2,428	2,428	2,428		

NOTE: This example illustrates that the model can result in higher emissions for an IFRT than for an EFRT when:
- **the tank color is other-than white,**
- **the tank is very large,**
- **the solar insolation is high, and**
- **the temperature of the stock liquid is high.**

Example 4: Crude Oil, six-foot leg height.

Stored liquid: **Crude Oil**

RVP	distillation slope	Antoine's Constants A	Antoine's Constants B	Liquid Temp Tla	TVP	Liquid Density Wl	Atmos Pressure Pa	P*	Mv	Ideal Gas Constant R
5	**na**	11.263	5,303.9	**60**	2.90	**7.1**	**14.7**	0.0548	**50**	10.731
				(deg F)	(psia)	(lb/gallon)	(psia)		(lb/lb-mole)	(psia ft^3) / (lb-mole R)

Tank Diameter	**100**	feet
height of deck above the bottom of the tank shell (leg height setting)	**6**	feet
height of liquid (for cases with a liquid heel)	**1**	feet

Determination of vapor space expansion factor:

delta(Pb) =	**0**	assumes freely vented vapor space
I =	**1370**	average value for continental US
alpha =	**0.17**	tank paint: **white, good condition**
delta(Ta) =	**20**	average value for continental US
delta(Tv) =	20.9	calculated from above
Ke =	0.091	vapor space expansion factor (calculated)

Loss (pounds per event) — Days Idle Prior to Refill

Equation		1	2	3		
	IFRT with full liquid heel	cumulative standing-idle loss				
5	**Standing Idle (breathing):**	**52**	**104**	**157**	**Ks = 0.57**	equation 8.
	resident vapors under the deck:	577	577	577	Sa = 0.57	arrival component of filling loss.
	add'l generated during filling:	35	35	35	Sg = 0.03	generated component of filling loss.
20	(count only on day of refill) **Filling:**	**612**	**612**	**612**	**total S = 0.60**	
	Total:	664	716	768		
	IFRT with partial liquid heel	cumulative standing-idle loss				
5	**Standing Idle (breathing):**	**46**	**92**	**138**	**Ks = 0.50**	equation 8.
	resident vapors under the deck:	510	510	510	Sa = 0.50	arrival component of filling loss.
	add'l generated during filling:	0	0	0	Sg = 0.00	generated component of filling loss.
20	(count only on day of refill) **Filling:**	**510**	**510**	**510**	**total S = 0.50**	
	Total:	556	602	648		
	EFRT with full liquid heel	cumulative standing-idle loss				
14	**Standing Idle (wind driven):**	**156**	**312**	**469**		
	resident vapors under the deck:	363	363	363	Sa = 0.36	arrival component of filling loss.
	add'l generated during filling:	153	153	153	Sg = 0.15	generated component of filling loss.
21	(count only on day of refill) **Filling:**	**516**	**516**	**516**	**total (Csf S) = 0.51**	equation 24;
	Total:	672	828	984		where Csf is from equation 23 and S = 0.6
	EFRT with partial liquid heel	cumulative standing-idle loss				
14	**Standing Idle (wind driven):**	**156**	**312**	**469**		
	resident vapors under the deck:	256	256	256	Sa = 0.25	arrival component of filling loss.
	add'l generated during filling:	153	153	153	Sg = 0.15	generated component of filling loss.
21	(count only on day of refill) **Filling:**	**409**	**409**	**409**	**total (Csf S) = 0.40**	equation 24;
	Total:	565	721	877		where Csf is from equation 23 and S = 0.5
	IFRT or EFRT, drain dry	cumulative standing-idle loss (no add'l standing idle loss after the first day)				
18	**Standing Idle (clingage):**	**351**	**351**	**351**		
	resident vapors under the deck:	351	351	351		arrival component incl. w/Standing Idle.
	add'l generated during filling:	183	183	183	S = 0.15	generated component of filling loss.
20	(count only on day of refill) **Filling:**	**183**	**183**	**183**	**total S = 0.15**	
	Total:	535	535	535		

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Example 5: Diesel, three-foot leg height.

Stored liquid: **Diesel**				Liquid		Liquid	Atmos			Ideal Gas
	distillation	Antoine's Constants		Temp		Density	Pressure			Constant
RVP	slope	A	B	Tla	TVP	Wl	Pa	P*	Mv	R
		12.101	8,907.0	**60**	0.007	**7.1**	**14.7**	0.0001	**130**	10.731
				(deg F)	(psia)	(lb/gallon)	(psia)		(lb/lb-mole)	(psia ft^3) / (lb-mole R)

Tank Diameter **100** feet

height of deck above the bottom of the tank shell
(leg height setting) **3** feet
height of liquid (for cases with a liquid heel)
1 feet

Determination of vapor space expansion factor:

delta(Pb) =	**0**	assumes freely vented vapor space
I =	**1370**	average value for continental US
alpha =	**0.17**	tank paint: **white, good condition**
delta(Ta) =	**20**	average value for continental US
delta(Tv) =	20.9	calculated from above
Ke =	0.040	vapor space expansion factor (calculated)

Loss (pounds per event) — Days Idle Prior to Refill

Equation		1	2	3		
	IFRT with full liquid heel	cumulative standing-idle loss				
5	**Standing Idle (breathing):**	**0.1**	**0.1**	**0.2**	**Ks = 0.60**	equation 8.
	resident vapors under the deck:	1.4	1.4	1.4	Sa = 0.60	arrival component of filling loss.
	add'l generated during filling:	0.0	0.0	0.0	Sg = 0.00	generated component of filling loss.
20	(count only on day of refill) **Filling:**	**1.4**	**1.4**	**1.4**	**total S = 0.60**	
	Total:	1.5	1.6	1.6		
	IFRT with partial liquid heel	cumulative standing-idle loss				
5	**Standing Idle (breathing):**	**0.0**	**0.1**	**0.1**	**Ks = 0.50**	equation 8.
	resident vapors under the deck:	1.2	1.2	1.2	Sa = 0.50	arrival component of filling loss.
	add'l generated during filling:	0.0	0.0	0.0	Sg = 0.00	generated component of filling loss.
20	(count only on day of refill) **Filling:**	**1.2**	**1.2**	**1.2**	**total S = 0.50**	
	Total:	1.2	1.3	1.3		
	EFRT with full liquid heel	cumulative standing-idle loss				
14	**Standing Idle (wind driven):**	**0.8**	**1.7**	**2.5**		
	resident vapors under the deck:	0.3	0.3	0.3	Sa = 0.14	arrival component of filling loss.
	add'l generated during filling:	0.4	0.4	0.4	Sg = 0.15	generated component of filling loss.
21	(count only on day of refill) **Filling:**	**0.7**	**0.7**	**0.7**	**total (Csf S) = 0.29**	equation 24;
	Total:	1.5	2.4	3.2		where Csf is from equation 23 and S = 0.6
	EFRT with partial liquid heel	cumulative standing-idle loss				
14	**Standing Idle (wind driven):**	**0.8**	**1.7**	**2.5**		
	resident vapors under the deck:	0.1	0.1	0.1	Sa = 0.04	arrival component of filling loss.
	add'l generated during filling:	0.4	0.4	0.4	Sg = 0.15	generated component of filling loss.
21	(count only on day of refill) **Filling:**	**0.5**	**0.5**	**0.5**	**total (Csf S) = 0.19**	equation 24;
	Total:	1.3	2.1	2.9		where Csf is from equation 23 and S = 0.5
	IFRT or EFRT, drain dry	cumulative standing-idle loss (no add'l standing idle loss after the first day)				
18	**Standing Idle (clingage):**	**2.2**	**2.2**	**2.2**		
	resident vapors under the deck:	2.2	2.2	2.2		arrival component incl. w/Standing Idle.
	add'l generated during filling:	0.5	0.5	0.5	S = 0.15	generated component of filling loss.
20	(count only on day of refill) **Filling:**	**0.5**	**0.5**	**0.5**	**total S = 0.15**	
	Total:	2.7	2.7	2.7		

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