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EVAPORATIVE LOSS FROM STORAGE TANKS

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TABLE OF CONTENTS

SECTION	DESCRIPTION	PAGE
	ABSTRACT	v
1.0	INTRODUCTION	1-1
2.0	LOSS SOURCES	2-1
	2.1 EFRT Loss Sources	2-1
	2.1.1 EFRT Rim Seals	2-2
	2.1.2 EFRT Roof Fittings	2-3
	2.1.3 EFRT Stock Clingage	2-4
	2.2 IFRT Loss Sources	2-4
	2.2.1 IFRT Rim Seals	2-6
	2.2.2 IFRT Roof Fittings	2-6
	2.2.3 IFRT Stock Clingage	2-7
	2.2.4 IFRT Roof Seams	2-7
	2.3 FRT Loss Sources	2-8
	2.3.1 FRT Roof Fittings	2-8
3.0	LOSS MECHANISMS	3-1
	3.1 Boiling	3-2
	3.2 Breathing	3-2
	3.3 Clingage	3-3
	3.4 Convection	3-3
	3.5 Desorption	3-4
	3.6 Diffusion	3-4
	3.7 Displacement	3-4
	3.8 Permeation	3-5
	3.9 Wicking	3-5
4.0	LOSS MEASUREMENT METHODS	4-1
	4.1 Field Tank Tests	4-1
	4.1.1 Stock Density Change Method	4-1
	4.1.2 Vented Vapor Measurement Method	4-2
	4.2 Pilot Tank Tests	4-3
	4.3 Wind Tunnel Tests	4-4
	4.4 Stock Clingage Tests	4-5
5.0	EFRT AND IFRT LOSS CALCULATION METHODS	5-1
	5.1 EFRT and IFRT Loss Equations	5-2
	5.2 Rim Seal Loss Factor	5-4
	5.3 Roof Fitting Loss Factor	5-4
	5.4 Roof Seam Loss Factor	5-5
	5.5 Product Factor	5-5
	5.6 Stock Clingage Factor	5-6

TABLE OF CONTENTS (Continued)

SECTION	DESCRIPTION	PAGE
6.0	FRT LOSS CALCULATION METHODS	6-1
	6.1 FRT Loss Equations	6-1
	6.2 Vapor Space Expansion Factor	6-3
	6.3 Vented Vapor Saturation Factor	6-6
	6.4 Working Loss Turnover Factor	6-7
	6.5 Working Loss Product Factor	6-8
7.0	SAMPLE CALCULATIONS	7-1
8.0	CONCLUSIONS	8-1
	REFERENCES	R-1
	NOMENCLATURE	R-3

LIST OF FIGURES

FIGURE	DESCRIPTION	PAGE
1.	Typical External Floating-Roof Tank (EFRT) With a Pontoon Floating Roof	F-1
2.	Typical External Floating-Roof Tank (EFRT) With a Double-Deck Floating Roof	F-1
3.	Mechanical-Shoe Primary Seal With a Rim-Mounted Secondary Seal	F-2
4.	Liquid-Mounted Resilient-Filled (Liquid-Filled) Primary Seal With a Rim-Mounted Secondary Seal	F-2
5.	Liquid-Mounted Resilient-Filled (Foam-Filled) Primary Seal With a Rim-Mounted Secondary Seal	F-2
6.	Vapor-Mounted Resilient-Filled (Foam-Filled) Primary Seal With a Rim-Mounted Secondary Seal	F-2
7.	Access Hatch	F-3
8.	Rim Vent	F-3
9.	Gauge-Hatch/Sample Well	F-3
10.	Vacuum Breaker	F-3
11.	Gauge-Float Well	F-3
12.	Roof Leg	F-4
13.	Overflow Roof Drain	F-4
14.	Unslotted Guide-Pole Well	F-4
15.	Slotted Guide-Pole/Sample Well	F-4
16.	Typical Internal Floating-Roof Tank (IFRT) With a Welded Floating Roof	F-5
17.	Typical Fixed-Roof Tank (FRT)	F-5
18.	Daily Ambient Heating-Related Breathing Loss Mechanism on a FRT	F-6
19.	Wind-Related Convection Loss Mechanism on an EFRT With a Vapor-Mounted Resilient-Filled Seal	F-6
20.	Field Tank Tests Using the Stock Density Change Method	F-7
21.	Stock Density Change From Field Tank Tests	F-7
22.	Field Tank Tests Using the Vented Vapor Measurement Method	F-7
23.	Photograph of the Pilot Tank Test Facility	F-8
24.	Schematic Diagram of the Pilot Tank Test Facility	F-8
25.	Photograph of the Wind Tunnel Test Facility	F-9
26.	Schematic Diagram of the Wind Tunnel Test Facility	F-9
27.	Photograph of the Stock Clingage Test Facility	F-10
28.	Schematic Diagram of the Stock Clingage Test Facility	F-10
29.	EFRT Rim Seal Loss Factor, F_R (lb-mole/ft yr), Versus Wind Speed for a Welded Tank With a Mechanical-Shoe Seal	F-11
30.	EFRT Rim Seal Loss Factor, F_R (lb-mole/ft yr), Versus Wind Speed for a Welded Tank With a Liquid-Mounted Resilient-Filled Seal	F-11
31.	EFRT Rim Seal Loss Factor, F_R (lb-mole/ft yr), Versus Wind Speed for a Welded Tank With a Vapor-Mounted Resilient-Filled Seal	F-11
32.	EFRT Rim Seal Loss Factor, F_R (lb-mole/ft yr), Versus Wind Speed for a Riveted Tank With a Mechanical-Shoe Seal	F-11
33.	Vented Vapor Saturation Factor, K_S (dimensionless)	F-12
34.	Working Loss Turnover Factor, K_N (dimensionless)	F-12

LIST OF TABLES

TABLE	DESCRIPTION	PAGE
1.	EFRT Rim Seal Loss Factor, F_R (lb-mole/ft yr), for Average-Fitting Seals	T-1
2.	IFRT Rim Seal Loss Factor, F_R (lb-mole/ft yr), for Average-Fitting Seals	T-1
3.	EFRT Roof Fitting Loss Factor, F_F (lb-mole/yr), for Typical Construction Details	T-2
4.	IFRT Roof Fitting Loss Factor, F_F (lb-mole/yr), for Typical Construction Details	T-2
5.	Clingage Factor, C (bbl/1000 ft^2)	T-3
6.	Solar Absorptance, α (dimensionless)	T-3
7.	Assumed Conditions for Floating-Roof Tank Sample Problem	T-3
8.	Evaporative Loss (lb/yr) for Each Floating-Roof Tank Loss Source Component	T-4
9.	Total Evaporative Loss (lb/yr) for Floating-Roof Tank Sample Problem	T-5

ABSTRACT

This year (1991) the American Petroleum Institute (API) completed the cycle of updating all three of the core evaporative loss publications that deal with aboveground storage tanks. These publications deal with evaporative losses from External Floating-Roof Tanks (EFRTs), Internal Floating-Roof Tanks (IFRTs) and Fixed-Roof Tanks (FRTs). The updated API evaporative loss publications are the result of an extensive API-sponsored laboratory and field testing program that included analytical developments to model storage tank evaporative loss processes. These revised API publications now permit loss calculations to be made with greater detail and accuracy for alternative loss control options.

This paper gives an overview of the API-sponsored work and discusses the areas of: (1) loss sources; (2) loss mechanisms; (3) loss measurement methods; (4) loss calculation methods; (5) sample calculations; and (6) conclusions related to the impact that these updated publications will have on petroleum industry storage tank evaporative losses.

1.0 INTRODUCTION

The American Petroleum Institute (API) Committee on Evaporation Loss Measurement (CELM) prepares, maintains and revises, as required, all API publications that provide methods for calculating evaporative losses from the storage and transfer of petroleum liquids.

API Publications 2517[1], 2518[2] and 2519[3] deal respectively with evaporative losses from External Floating-Roof Tanks (EFRTs), Fixed-Roof Tanks (FRTs) and Internal Floating-Roof Tanks (IFRTs). These three publications were originally issued in 1962 and were then intended to provide petroleum company operating personnel with a basis to evaluate the benefits associated with alternative product conservation techniques.

With the establishment of the U.S. Clean Air Act in 1970, attention was focused on atmospheric emissions from hydrocarbon sources. Recognizing that technological improvements in petroleum storage tank construction and operation had occurred since the time that the original evaporative loss data was obtained, the CELM was formally reorganized in 1974 to initiate a program to update these loss publications. A preliminary evaluation indicated that the then existing API evaporative loss calculation methods significantly overestimated hydrocarbon losses, or atmospheric emissions.

Initial API efforts were directed at updating API Publications 2517 and 2519, which deal with floating-roof tanks. More recent efforts have been directed at updating API Publication 2518, which deals with fixed-roof tanks, and the Second Edition will be issued in the Fall of 1991. All of these efforts involved an extensive laboratory and field testing program that included analytical developments to model storage tank evaporative loss processes. The API results have also become the basis for the U.S. Environmental Protection Agency publication [4] on air pollutant emission factors.

This paper describes the efforts that were directed toward updating the API evaporative loss publications that deal with EFRTs, IFRTs and FRTs. An overview is given of:

- Loss Sources
- Loss Mechanisms
- Loss Measurement Methods
- Loss Calculation Methods
- Sample Calculations

The API evaporative loss publications will soon be converted to metric units. This paper, however, presents the API loss calculation methods in the units currently used so that the description presented here may be compared directly with the current versions of the API loss publications.

2.0 LOSS SOURCES

A tank "loss source" may be defined as a basic element of the tank from which evaporative loss, or atmospheric emissions, occurs. For each tank type, the potential loss sources are:

External Floating-Roof Tanks (EFRTs)

- o Rim Seals
- o Roof Fittings
- o Stock Clingage

Internal Floating-Roof Tanks (IFRTs)

- o Rim Seals
- o Roof Fittings
- o Roof Seams
- o Stock Clingage

Fixed-Roof Tanks (FRTs)

- o Roof Fittings

To better understand these loss sources, it is helpful to review some of the loss-related tank construction details.

2.1 EFRT Loss Sources

Figures 1 and 2 show typical EFRTs. EFRTs are vertical cylindrical vessels which do not have a fixed roof over the top of the tank, but which utilize an External Floating Roof (EFR) that rests on the stock liquid surface.

EFRs are currently of two general types:

- o Pontoon Floating Roof (see Figure 1)
- o Double-Deck Floating Roof (see Figure 2)

The pontoon floating roof incorporates buoyancy chambers that assist in keeping the roof floating, even under heavy water or snow loads. One type of

design uses an annular ring of pontoons around the outer perimeter of the floating roof. In this design, the center single deck area is designed to balloon upward to contain stock vapors that are generated from ambient heating of the stock liquid surface under the floating roof. The amount of surface heating, however, is reduced by the insulating effect of the double-deck in the pontoon area and by the ballooning effect of the center single deck.

The double-deck floating roof incorporates two decks which cover the entire area of the floating roof. Vertical bulkheads are used to support the upper deck and to divide the space between the decks into separate liquid-tight compartments. The double-deck floating roof provides good stability, but smaller rainwater load carrying capacity than the pontoon floating roof. The top deck, which extends over the entire area of the floating roof, provides an insulating air space between the decks and thus minimizes heating of the stock liquid surface.

EFRs are typically of welded construction, and the roof seams are thus not a source of evaporative loss.

2.1.1 EFRT Rim Seals

An EFRT rim seal system consists of either one or two separate seals. The lower, or first seal, is called the primary seal; the upper, or second seal, is called the secondary seal.

Figures 3 through 6 show typical primary and secondary seal systems for EFRTs with welded tank construction. For riveted tank construction, the only primary seal typically used is the mechanical-shoe primary seal due to its good durability when sliding on a riveted surface.

Two basic types of primary seals are currently in widespread use for welded tank construction:

- Mechanical-Shoe Primary Seal (see Figure 3)
- Resilient-Filled Primary Seal (see Figures 4, 5 and 6)

The resilient-filled primary seal may be mounted so that it either touches the liquid surface (i.e. liquid-mounted) or allows for a vapor space between the bottom of the seal envelope and the liquid surface (i.e. vapor-mounted). The resilient-filled seal may be filled with liquid, resilient foam, or gas to expand the seal envelope and maintain contact with the tank shell.

Two types of secondary seals are used:

- Shoe-Mounted Secondary Seal (see Figures 3, 4, 5 and 6)
- Rim-Mounted Secondary Seal (not shown)

Shoe-mounted secondary seals are attached to the top of the shoe on a mechanical-shoe primary seal. They are effective in controlling emissions from gaps between the tank shell and the shoe, but do not control emissions from the primary seal fabric. Rim-mounted secondary seals, however, are more effective in controlling emissions since they cover the entire rim space, and are more commonly used than shoe-mounted secondary seals.

Weather shields are sometimes used with a resilient-filled primary seal to protect the primary seal fabric from deterioration due to exposure to weather, debris and sunlight. Weather shields are usually of a leaf-type construction and have numerous radial joints to allow for movement of the floating roof and for irregularities in the tank shell. They are less effective than rim-mounted secondary seals in reducing evaporative loss due primarly to the unsealed radial joints.

2.1.2 EFRT Roof Fittings

As a result of an API-sponsored test program that was performed by CBI in 1984 [5,6], a method was developed for calculating the evaporative loss from roof fittings commonly used on EFRTs. These results were incorporated into the Third Edition of API Publication 2517 [1].

Roof fitting loss factors have been developed for the following types of EFRT roof fittings:

ROOF FITTING TYPE	FIGURE NUMBER
Access Hatch	7
Rim Vent	8
Gauge-Hatch/Sample Well	9
Vacuum Breaker	10
Roof Leg	12
Gauge-Float Well	11
Overflow Roof Drain	13
Unslotted Guide-Pole Well	14
Slotted Guide-Pole/Sample Well	15

The above list of EFRT roof fitting types is arranged in order of generally increasing evaporative loss potential. Section 3.4 of Reference [1] provides a detailed description of each of these roof fitting types.

2.1.3 EFRT Stock Clingage

Evaporative loss from stock clingage occurs from an EFRT when stock is withdrawn from the tank. As the floating roof level decreases, liquid stock tends to cling to the inside surface of the tank shell. When the floating-roof rim seal passes downward and exposes the wetted portion of the tank shell inside surface, the volatile portion of the stock clingage evaporates, resulting in evaporative loss.

2.2 IFRT Loss Sources

Figure 16 shows a typical IFRT. IFRTs are vertical cylindrical vessels which have both a fixed roof over the top of the tank and an Internal Floating Roof (IFR) that rests on the stock liquid surface. The fixed roof may be either "column supported" (i.e. with vertical support columns in the tank) or "self-supported" (i.e. without vertical support columns).

To reduce the occurrence of a flammable vapor-air mixture in the tank vapor space between the floating roof and the fixed roof, vents are installed at the

top of the tank shell and on the fixed roof to provide natural circulation of air through the vapor space. Such tanks are referred to as "freely vented" IFRTs.

IFRs are currently of two general types:

- Welded Roofs
- Bolted Roofs (i.e. Mechanically Joined Roofs)

Welded floating roofs consist of steel plates which are welded together along their edges to form a continuous deck. A vertical rim plate is provided around the perimeter of the floating roof to which the rim seal system is attached. Floatation occurs as a result of displacement of the liquid stock by the floating roof. Floatation may be enhanced by the use of buoyant volumes on the top surface of the floating roof, and these may take the form of an annular ring similar to a pontoon type EFR.

Bolted floating roofs may be either "non-contact" or "contact" type. Non-contact bolted floating roofs consist of thin sheets (typically aluminum) which are mechanically fastened to a supporting grid framework, below which the stock vapor is contained. A vertical rim, or skirt, extends down from the perimeter of the floating roof into the stock liquid to help contain the stock vapors under the floating roof. Floatation is provided by the use of sealed tubular pontoons that are attached to the underside of the floating roof.

Contact bolted floating roofs consist of sealed panels which are mechanically joined along their edges to form a continuous roof. A vertical rim extends upward from the perimeter of the floating roof to which the rim seal system is attached. The roof panels float directly on the stock liquid surface and are typically aluminum or fiberglass reinforced polyester skin sandwich panels with either a honeycomb aluminum core or a rigid foam core.

Some IFRTs were originally constructed as EFRTs and were later converted to IFRTs by covering them with a fixed roof and adding shell and roof vents to provide ventilation of the tank vapor space. For this type of IFRT, the

construction details of the rim seals and roof fittings are identical to those described in Section 2.1 for EFRTs.

2.2.1 IFRT Rim Seals

IFR rim seal systems are similar to EFR rim seal systems in that they may include both a primary seal and a secondary seal.

Three basic types of primary seals are currently in widespread use for welded tank construction:

- Mechanical-Shoe Primary Seal (see Figure 3)
- Resilient-Filled Primary Seal (see Figures 4, 5 and 6)
- Flexible-Wiper Primary Seal (not shown)

Construction details of the mechanical-shoe primary seal and the resilient-filled primary seal were described in Section 2.1.1. The flexible-wiper primary seal consists of a continuous annular blade of flexible material that is fastened to the floating roof rim and which spans the rim space and contacts the tank shell.

Secondary seals are sometimes used to provide additional evaporative loss control on IFRTs. As was previously described in Section 2.1.1 for an EFRT, the secondary seal on an IFRT may also be either rim-mounted or shoe-mounted. However, rim-mounted secondary seals are more commonly used. The secondary seal may be either a resilient-filled seal or a flexible-wiper seal.

2.2.2 IFRT Roof Fittings

Roof fitting loss factors have been developed for the following types of IFRT roof fittings.

ROOF FITTING TYPE	FIGURE NUMBER
Vacuum Breaker	10
Stub Drain	--
Access Hatch	7
Roof Leg	12
Gauge-Float Well	11
Column Well	14
Unslotted Guide-Pole Well	14
Slotted Guide-Pole/Sample Well	15
Ladder Well	--

The above list of IFRT roof fitting types is arranged in order of generally increasing evaporative loss potential. Section 2.4 of Reference [3] provides a detailed description of each of these roof fitting types. There are other types of IFRT roof fittings that are used, but which do not penetrate the IFR, and these are not potential sources of evaporative loss.

2.2.3 IFRT Stock Clingage

Evaporative loss from stock clingage occurs from an IFRT when stock is withdrawn from the tank. As the floating roof level decreases, liquid stock tends to cling to the inside surface of the tank shell and to the surface of any fixed roof support columns, guide poles and fixed ladders. When the floating-roof rim seal or column well cover passes downward and exposes the wetted portions of the tank shell and support columns, the volatile portion of the stock clingage evaporates, resulting in evaporative loss.

2.2.4 IFRT Roof Seams

IFRs are constructed with either welded seams or bolted seams (i.e. mechanically joined seams). To the extent that these bolted seams are not vapor tight, they are a source of evaporative loss. Welded seams are vapor tight and are thus not a source of evaporative loss.

2.3 FRT LOSS SOURCES

Figure 17 shows a typical FRT. FRTs are vertical cylindrical vessels that have a fixed roof. The fixed roof may be column-supported or self-supported, and may be cone-shaped, dome-shaped or flat.

Some fixed-roof tanks incorporate an internal floating roof, but do not have shell vents. These type of storage tanks are called closed floating-roof tanks (CFRTs). The method of calculating evaporative losses from CRFTs is currently not covered by any API Loss Publication.

A fixed-roof tank will accommodate only a very low internal pressure or vacuum. For tanks built in accordance with API Standard 650 [7], the maximum safe working pressure or vacuum for large tanks is usually 1-1/2 inches of water column, or approximately 1 ounce per square inch.

2.3.1 FRT Roof Fittings

Roof fittings commonly found on a FRT include:

- Access Hatch
- Float Gauge
- Gauge-Hatch/Sample Well
- Pressure-Vacuum Vent

Section 3.3 of Reference [2] provides a detailed description of each of these roof fitting types. The evaporative loss calculation procedures for an FRT includes evaporative loss from only the pressure-vacuum vent since the loss contribution of the other roof fittings is negligible in comparison to that from the pressure-vacuum vent.

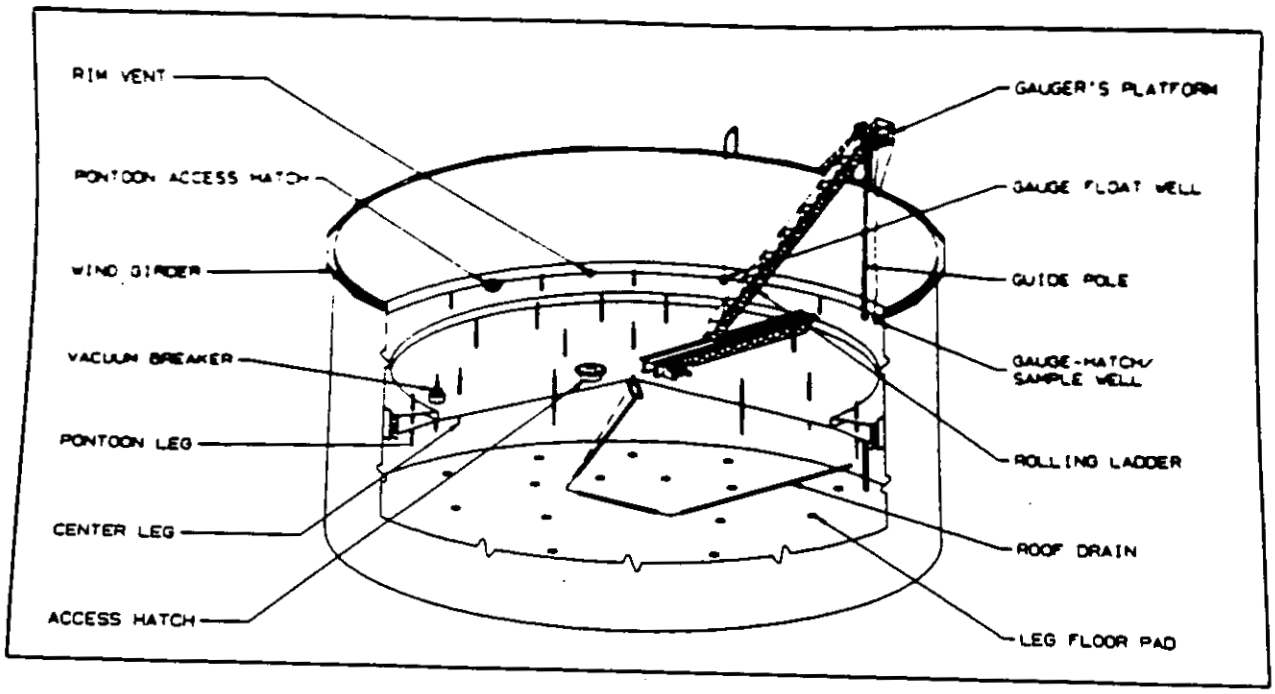

Figure 1 - Typical External Floating-Roof Tank (EFRT) With a Pontoon Floating Roof

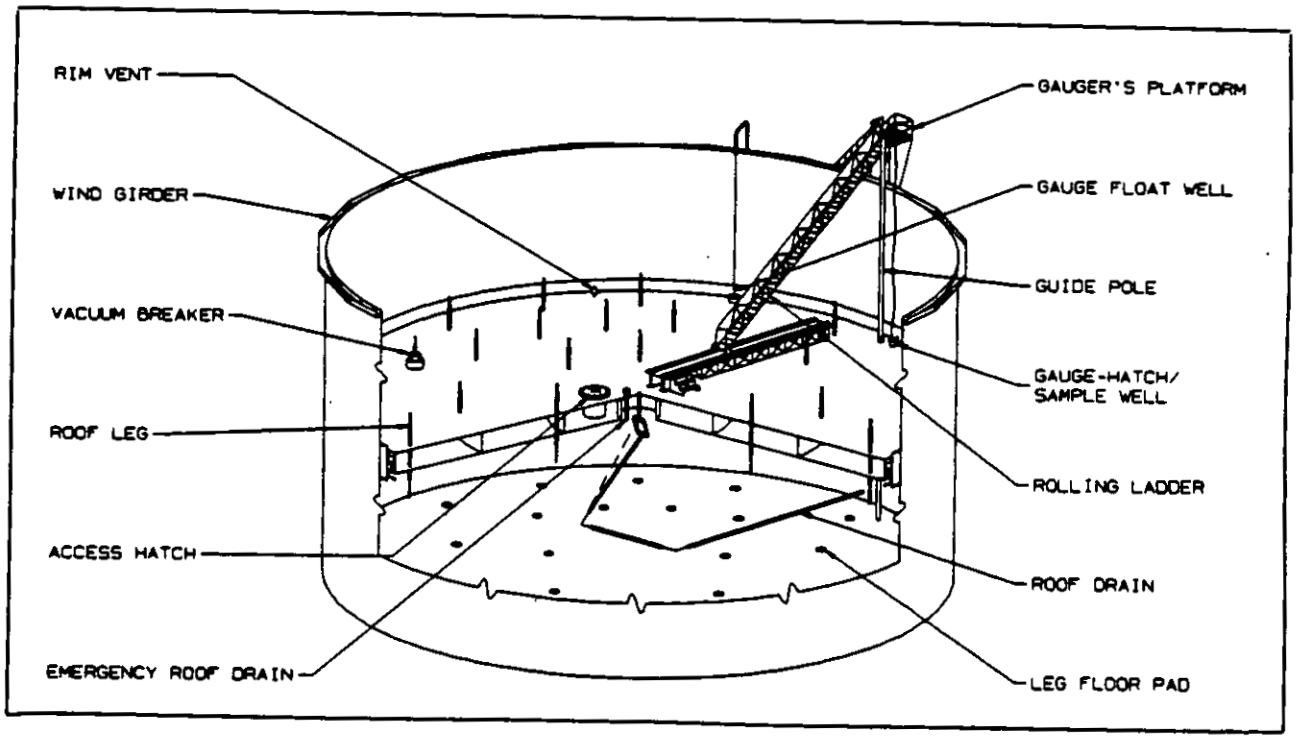

Figure 2 - Typical External Floating-Roof Tank (EFRT) With a Double-Deck Floating Roof

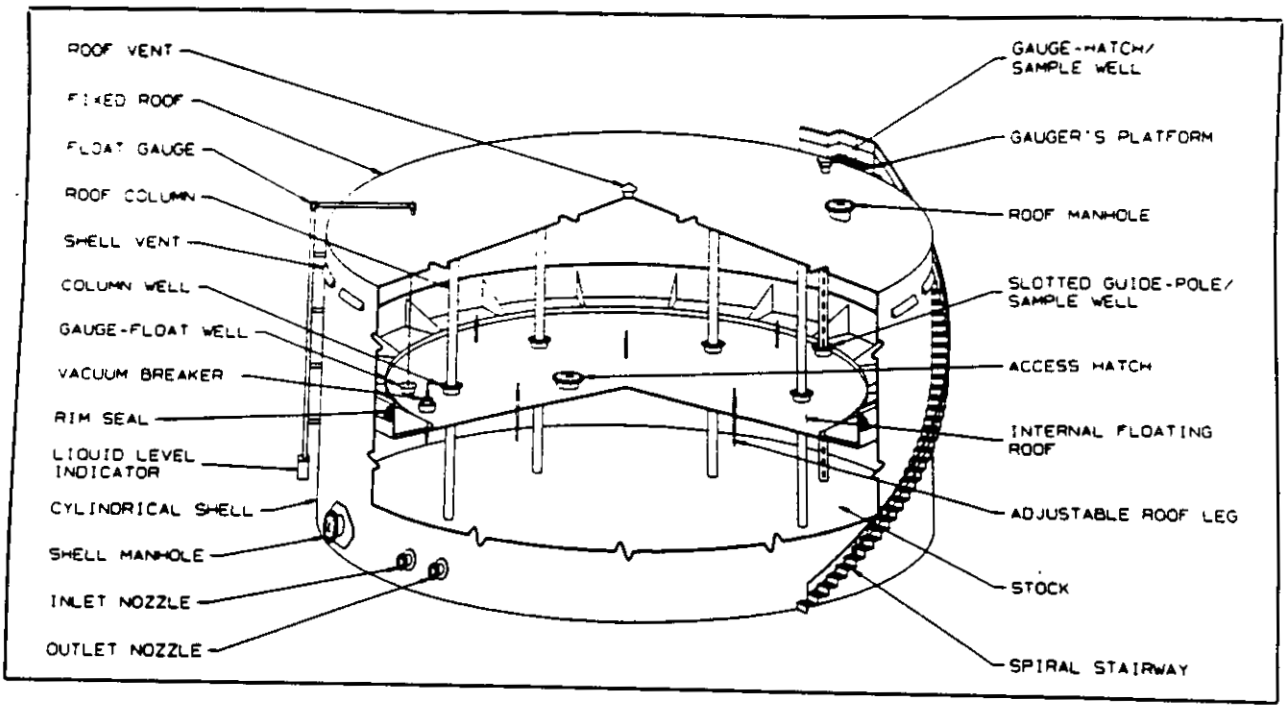

Figure 16 - Typical Internal Floating-Roof Tank (IFRT) With a Welded Floating Roof

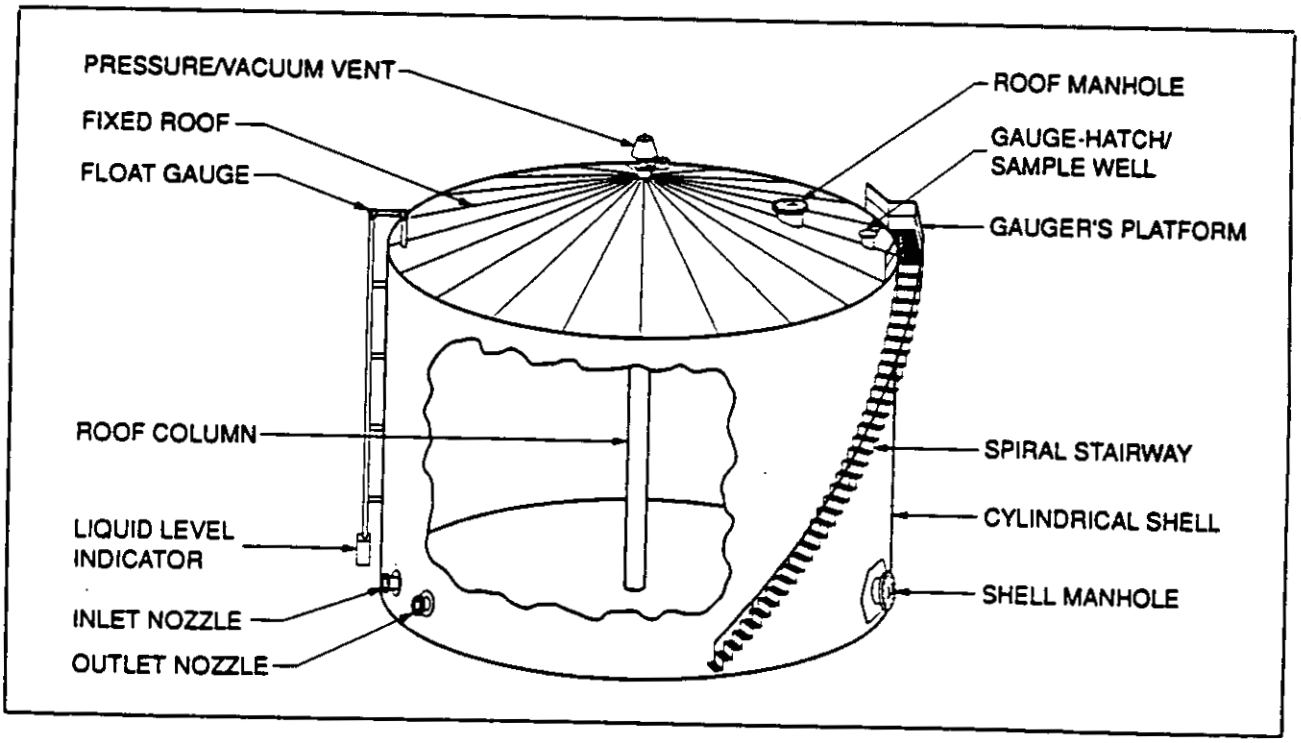

Figure 17 - Typical Fixed-Roof Tank (FRT)

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3.0 LOSS MECHANISMS

A storage tank "loss mechanism" may be defined as a physical or chemical process involved in the evaporative loss of stock. For the EFRT, IFRT and FRT loss sources listed in Section 2, several loss mechanisms have been identified [6]:

- Boiling
- Breathing
- Clingage
- Convection
- Desorption
- Diffusion
- Displacement
- Permeation
- Wicking

Generally, losses from a particular loss source involve several loss mechanisms acting simultaneously, and it is difficult when interpreting loss measurement data to separate the individual contribution of each loss mechanism. However, for purposes of better understanding the process of evaporative loss and its associated loss parameters, it is useful to have some understanding of these loss mechanisms.

Operation of a storage tank is generally divided into two modes:

- Standing Storage
- Working Storage

In standing storage, stock does not flow into or out of the storage tank; in working storage, stock does flow into or out of the storage tank. The loss sources and loss mechanisms involved in these two modes of operation are not the same.

3.1 Boiling

Boiling occurs when the stock surface true vapor pressure equals or exceeds atmospheric pressure, and involves the rapid evolution of vapor from the liquid surface.

Although boiling is a potential loss mechanism, storage tanks are normally operated in a manner so as to avoid a boiling product. For this reason, the API loss calculation methods described in Sections 5 and 6 are not suitable for use with boiling or unstable stocks.

3.2 Breathing

Breathing is the process in which stock vapors are expelled from an enclosed volume that is in communication with the stock liquid surface, and is due to either a vapor temperature increase, evaporation from the stock liquid surface or a barometric pressure decrease.

Breathing can occur, for example, in the vapor space of a FRT during standing storage. Figure 18 illustrates the daily, ambient heating-related, breathing loss mechanism on a FRT that is partially filled with a volatile liquid stock and is equipped with a pressure-vacuum vent. During the daily ambient heating cycle, the gas mixture in the tank vapor space is heated from a minimum temperature condition to a maximum temperature condition. Vapor is vented from the tank vapor space when the vapor space pressure increases to the pressure setting of the pressure-vacuum vent, resulting in evaporative loss.

As the gas mixture in the tank vapor space is cooled from a maximum temperature condition to a minimum temperature condition, air is admitted to the tank vapor space when the pressure decreases to the vacuum setting of the pressure-vacuum vent. Evaporation of stock occurs from the liquid surface as the stock tries to saturate the air that was admitted to the tank vapor space. Test data indicates that there typically is a region at the top of the tank vapor space near the pressure-vacuum vent where there is a significant concentration gradient. The vented gas is typically not saturated (i.e.

contains less stock vapor per unit volume than the gas immediately above the liquid surface).

3.3 Clingage

Clingage involves the tendency for liquid stock to adhere to a surface once it has had contact with that surface.

Clingage can occur, for example, when stock is withdrawn from an EFRT or IFRT. As the floating roof level decreases, liquid stock tends to cling to the inside surface of the tank shell and to the fixed roof vertical support columns. When the floating roof passes downward and exposes these areas, the volatile portion of the stock clingage rapidly evaporates, resulting in evaporative loss.

3.4 Convection

Convection is the process in which stock vapors are set into motion by temperature and/or pressure differences.

Convection can occur, for example, in the rim space around an EFRT. Figure 19 illustrates the wind-related convection loss mechanism on an EFRT with a vapor-mounted resilient-filled seal. As the wind flows over the floating roof, a pressure gradient is generated above the rim seal, with a higher pressure existing above the seal on the downwind side of the floating roof than on the upwind side. As a result of this pressure gradient, air tends to flow downward past the seal on the downwind side, flow circumferentially around the rim vapor space below the primary seal, and then flow upward past the seal on the upwind side of the floating roof. As the air flows circumferentially around the rim vapor space, it tends to become saturated with stock vapor. This vapor is then emitted with the air vented on the upwind side of the floating roof, resulting in evaporative loss.

3.5 Desorption

Desorption is the process in which dissolved gases come out of solution due to a liquid temperature increase or a barometric pressure decrease.

Desorption can occur, for example, in the rim space around a floating roof. Liquid stocks may contain some amount of dissolved volatile gases. As the stock temperature increases or the barometric pressure decreases, the amount of gas that can be dissolved in the stock will decrease and some gas will come out of solution, resulting in evaporative loss.

3.6 Diffusion

Vapor diffusion is the process in which components in a vapor state tend to distribute equally throughout the vapor space.

Vapor diffusion can occur, for example, in the gaps of a mechanical-shoe primary seal on an EFRT or IFRT. In the narrow vertical gap between the tank shell and the metallic shoe, upward diffusion of the stock vapor can occur, resulting in evaporative loss. Normally, however, vapor convection also occurs in these narrow vertical gaps, and the combined effect can result in much higher evaporative loss rate than the loss rate due to diffusion alone.

3.7 Displacement

Displacement is the process in which stock vapor is expelled from a fixed volume as stock liquid product fills the volume.

Displacement can occur, for example, in a FRT when it is being filled with stock. As the liquid level increases, air containing stock vapors is expelled from the tank pressure vent, resulting in evaporative loss.

3.8 Permeation

Permeation is the process in which stock vapor diffuses through a solid material due to a concentration difference across the material.

Permeation can occur, for example, through the seal envelope of a resilient-filled primary seal. The seal envelope material is normally a flexible coated fabric sheet (e.g. polyurethane coated nylon fabric). These materials may be somewhat permeable to product vapors. Since a higher concentration of vapor is normally present below the seal, vapors tend to permeate through the seal envelope material, resulting in evaporative loss.

3.9 Wicking

Wicking is the process in which a stock liquid tends to flow upward between two closely spaced surfaces by capillary action due to surface tension forces.

Wicking can occur, for example, with a liquid-mounted resilient-filled primary seal on an EFRT or IFRT. The primary seal envelope is normally in intimate contact with the inside surface of the tank shell. If the primary seal is liquid-mounted, the stock liquid level in the rim space may be located in the area of seal-to-shell contact. Depending upon the surface characteristics of the seal envelope and tank shell, certain high surface tension stocks may have a tendency to flow upward in the seal-to-shell contact area due to wicking, resulting in evaporative loss.

4.0 LOSS MEASUREMENT METHODS

Four types of evaporative loss measurement methods were used to obtain the test data for preparing the latest editions of API Publications 2517 [1], 2518 [2] and 2519 [3], for EFRTs, FRTs and IFRTs, respectively. These evaporative loss measurement methods are:

- o Field Tank Tests
- o Pilot Tank Tests
- o Wind Tunnel Tests
- o Stock Clingage Tests

4.1 Field Tank Tests

Two types of test methods were used on field tanks:

- o Stock Density Change Method (used on EFRTs and IFRTs)
- o Vented Vapor Measurement Method (used on FRTs).

4.1.1 Stock Density Change Method

The stock density change method was used to measure the standing storage loss from two field EFRTs and one field IFRT [9]. This method was also used in tests performed on the pilot test tank [10,11]. In this method, the stock density is accurately measured over a period of time. For multicomponent hydrocarbon stocks, the lighter components tend to evaporate faster, thus resulting in a gradual increase in the density of the remaining stock.

Figure 20 is a schematic of the stock density change method that was used in the API-sponsored field tank tests [9]. In these tests, three tanks were tested simultaneously. A mobile van housing the density meter and associated instrumentation was moved from one tank to another to sample each tank weekly over a period of about 120 days. Each tank was sampled at approximately 20 locations in the stock to determine the average stock density. A Mettler-Paar Model DMA 60/601 high-precision density meter was used to measure the density of stock samples to seven significant figures. This high degree of precision was

necessary because of the small change in stock density associated with the evaporative loss. Figure 21 illustrates how the average stock density changed with time during one of the field tank tests [9].

The stock density change measured in the field tank tests was converted to evaporative loss by using laboratory measurements of the stock properties that included the evaporative density-change factor [9].

4.1.2 Vented Vapor Measurement Method

The vented vapor measurement method was used to measure the evaporative loss from one field FRT storing fuel oil [12] as part of an API-sponsored test program. A simplified version of the vented vapor measurement method was also used in earlier field tank tests on 21 FRTs storing crude oils, distillates and fuel oil [13] and on 6 FRTs storing petrochemicals [14]. In this method, the evaporative loss is determined from measurements of the volume and composition of the vapor expelled from the FRT pressure vent.

Figure 22 is a schematic diagram of the test arrangement that was used on a 20 foot diameter field tank. The volume of vapor expelled through the pressure vent and the volume of air inhaled through the vacuum vent were measured using dry gas meters. The pressure vent gas meter was placed in an insulated and heated enclosure to prevent hydrocarbon condensation in the meter.

In addition to sampling the vapor which was passed through the pressure vent gas meter, the tank vapor space was sampled to determine the vertical profile of hydrocarbon concentration. Ten vertical points at 3 different locations were sequentially sampled (i.e. a total of 30 vapor sample points) to determine the daily variation in the concentration profile. These vapor samples were analyzed for total hydrocarbon concentration and periodically a complete component analysis was performed using a gas chromatograph.

The vertical temperature profile in the vapor space was measured with 20 vertical thermocouples at 3 different locations. In addition, the ambient temperature, tank roof temperature and the tank shell temperature were measured.

An extensive data acquisition system was used to aid in recording and analyzing the test results.

The daily evaporative loss of the tank was determined by summing the hourly amounts of hydrocarbon vapor expelled from the tank pressure vent.

4.2 Pilot Tank Tests

A Pilot Tank Test Facility was used to study evaporative losses from both EFRTs [15] and IFRTs [16]. Figure 23 is a photograph and Figure 24 is a schematic diagram of the CBI 20 foot diameter Pilot Tank Test Facility.

In this test method, a controlled quantity of air is passed through the space between a floating roof and a fixed roof to simulate the effect of ambient wind. For EFRT tests, the air flow rate was controlled to simulate the effect of ambient wind flowing across an EFRT. For IFRT tests, the air flow rate was controlled to simulate the effect of ambient wind blowing through the shell vents of an IFRT. Wind tunnel test data and field tank test data were used to establish the pilot tank wind speed calibration for an EFRT [17,18] and an IFRT [19]. The increase in total hydrocarbon concentration of the air passing through the pilot tank is measured, and the evaporative loss rate may then be directly calculated.

The main advantage of the pilot tank test method is that the test conditions may be controlled and systematically varied to study the effect of specific parameters on evaporative loss. Some of the test conditions that were systematically varied include [15]:

Tank Construction Conditions:

- Welded and Riveted Tank Shell Construction

Floating Roof Construction Conditions:

- EFRT and IFRT Primary Seal Type
- EFRT and IFRT Primary Seal Mounting Type
- EFRT and IFRT Primary Seal Gaps

- o EFRT and IFRT Secondary Seal Type
- o EFRT and IFRT Secondary Seal Mounting Type
- o EFRT and IFRT Secondary Seal Gaps

Meteorological Conditions:

- o Ambient Wind Speed
- o Ambient Temperature

Product Conditions:

- o Product Vapor Pressure
- o Product Types Including:
  - Gasoline,
  - Crude Oil,
  - Normal Hexane,
  - Benzene,
  - Normal Octane, and
  - Mixtures of Propane and Normal Octane.

Most of the test work was performed using mixtures of propane and normal octane, where the propane content was systematically controlled and varied to determine the effect of vapor pressure on evaporative loss.

4.3 Wind Tunnel Tests

A special Wind Tunnel Test Facility was constructed by CBI and used in an API-sponsored test program [20] to measure the evaporative loss of EFRT roof fittings. Figure 25 is a photograph and Figure 26 is a schematic diagram of the Wind Tunnel Test Facility. The wind tunnel is 29 feet long and has a 3 foot square cross section. It incorporates 4 test sections, each 5 feet long, for simultaneously testing 4 separate roof fittings.

Each of the roof fittings tested was a full-scale roof fitting that was mounted on a stock liquid reservoir which rested on a digital platform scale. The roof fittings extended above the test reservoirs into the wind tunnel. The ambient wind effect on the exposed portion of the roof fittings was simulated by the air flow through the wind tunnel. Air from a blower passed through a

transition section and an air distribution section prior to passing over the roof fittings. As evaporative loss occurred during a particular test, this loss was directly measured by the weight change recorded for each of the platform scales.

Evaporative loss measurements were performed at simulated wind speeds up to 14 mi/hr. A total of 8 series of tests, each series with 4 different roof fittings, were performed on the most common roof fittings used on current EFRTs.

4.4 Stock Clingage Tests

Figure 27 is a photograph and Figure 28 is a schematic diagram of the Stock Clingage Test Facility constructed by CBI. This test facility consisted of a test tank filled with stock and a test plate immersed in the stock. Withdrawal of stock from a floating-roof tank and the associated lowering of the floating roof was simulated by raising the test plate out of the test tank.

The test tank was fitted with a heat exchanger coil through which tempered water was passed to accurately control the temperature of the test fluid, or stock. Thermocouples were located at different elevations in the test tank to measure the stock temperature. The "necked-down" section of the test tank was fitted with a sight glass to allow measurement of the stock level in the test tank.

A structural framework was attached to the top of the test tank to support the test plate as it was drawn out of the test tank. The lifting mechanism consisted of a variable speed winch fitted with an automated control system. The control system maintained a constant lifting speed on the test plate. Limit switches were used to set the total range of vertical motion of the test plate and to reverse the winch direction. The winch speed was the same for both raising and lowering the test plate.

The upper portion of the test tank was fitted with a vapor-mounted resilient-filled primary seal to simulate the sealing system of a floating-roof tank. Two different types of seal fits were investigated. In the first type of

seal fit, there was no gap between the seal and the test plate, resulting in effective wiping action on the test plate. In the second type of seal fit, there was a gap between the seal and the test plate to simulate situations on a floating-roof tank where there is not a tight fit between seal and shell.

The test plate simulated the shell of a floating-roof tank. The test plate was approximately 20 feet long by 12 inches wide by 1/4 inch thick and was made of carbon steel. Both sides of the test plate were test surfaces. The edges of the test plate were beveled to permit complete wiping of the surfaces and to minimize stock clingage to the edges of the plate as it passed by the seals. The test plate was raised and lowered through a range of 16 feet - 9 inches. Since the plate was 1 foot wide and both sides were in contact with the stock and the seals, the total wiped surface area for each plate was 33.5 square feet. Two different test plate surface conditions were examined: a clean surface and a lightly rusted surface.

The evaporative loss due to shell clingage was determined by measuring the decrease in stock level in the test tank at the necked-down section. The test plate was raised out and lowered back into the test tank at a continuous rate of about 6 in/min. This process was performed for at least 20 cycles.

Two different stocks were tested: octane [21] and a low-viscosity, U.S. mid-continent, type A-B sweet crude oil [22].

5.0 EFRT AND IFRT LOSS CALCULATION METHODS

This section presents a brief outline of the evaporative loss calculation methods for both an EFRT and an IFRT.

The current API loss calculation methods for an EFRT, IFRT and FRT are contained in the following API evaporative loss publications:

TANK TYPE	API PUBLICATION
EFRT	API Publication 2517, Third Edition, February 1989
FRT	API Publication 2518, Second Edition, Fall 1991
IFRT	API Publication 2519, Third Edition, June 1983

Due to the similarities between the evaporative loss calculation methods for an EFRT and IFRT, they are described together in Section 5. The evaporative loss calculation method for a FRT is significantly different from that for an EFRT and IFRT due to the different loss mechanisms involved. Therefore, the evaporative loss calculation method for a FRT is described in Section 6.

It is not possible to give here all the details for each calculation method, and before using these methods it is recommended that a careful review be made of the above API publications. The following summary is intended only to indicate the basic format of each method and the loss parameters involved in each method.

The limitations under which the API evaporative loss methods can be used are listed in each of the appropriate API publications. Some of these limitations pertain to the applicable range of tank diameters, stock types, stock vapor pressures, wind speeds and loss estimation time periods. Also, the methods are not suitable to estimate evaporative losses from unstable or boiling stocks.

The current loss calculation methods for EFRTs and IFRTs are detailed and take into account the independent contribution of each loss source to the total loss for generic equipment types. This is useful in identifying the significant

parameters affecting the total loss for a specific tank as well as in evaluating the effectiveness of alternative loss reduction options.

The loss calculation equations are based on the use of both theoretical models of the significant loss mechanisms and experimental test results designed to isolate the effect of the significant loss parameters.

5.1 EFRT and IFRT Loss Equations

Total Loss

The total loss, L_T, is the sum of the withdrawal loss, L_W, and the standing storage loss, L_S, as shown in Equation 1:

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

Withdrawal Loss

The withdrawal loss, L_W, may be calculated from Equation 2:

$$L_W = (0.943)\left(\frac{Q\ C\ W_L}{D}\right)\left[1 + \left(\frac{N_C\ F_C}{D}\right)\right] \tag{2}$$

The withdrawal loss, L_W, will vary with tank operating practices. Industry-wide experience has found that this loss is often small, except in cases of high throughput that result in frequent tank turnovers (i.e. greater than about 10 turnovers per year) or in cases of a large clingage factor, such as for high viscosity crude oil.

The number of columns, N_C, is 0 for an EFRT.

Standing Storage Loss

The standing storage loss, L_S, may be calculated from Equation 3:

$$L_S = (F_R D + F_F + F_D)(P^* M_V K_C) \tag{3}$$

In the Third Edition of API Publication 2517 [1], the standing storage loss, L_S, calculation method was modified to incorporate the total roof fitting loss factor, F_F. Previously, the evaporative loss contribution of the roof fittings was assumed to be negligible.

Equation 3 involves the product of two terms:

First Term, $(F_R D + F_F + F_D)$

The first term pertain only to floating-roof construction parameters (e.g. rim seal system type, roof fitting types, roof seam construction type) and environmental parameters (e.g. ambient wind speed, V).

Second Term, $(P^* M_V K_C)$

The second term pertain only to stock characteristics (e.g. vapor pressure, vapor molecular weight, stock type).

The vapor pressure function, P^*, is defined by Equation 4.

$$P^* = \frac{\left(\frac{P}{P_A}\right)}{\left[1 + \left(1 - \frac{P}{P_A}\right)^{0.5}\right]^2} \tag{4}$$

where the stock vapor pressure, P, is determined at the stock liquid bulk temperature, T_B.

5.2 Rim Seal Loss Factor

The rim seal loss factor, F_R, for EFRTs has been found to depend upon the tank construction type, rim seal system type, seal fit, and ambient wind speed, V. Figures 29 through 32 present the rim seal loss factor for different sealing systems as a function of wind speed, V, between 2 and 15 mi/hr (i.e. the wind speed range of the test data). Table 1 lists the EFRT rim seal loss factor for average-fitting seals at 5, 10 and 15 mi/hr wind speeds. The loss control effectiveness of different rim seal systems can be compared by comparing the rim seal loss factors, F_R, at the same wind speed, V.

The rim seal loss factor, F_R, for IFRTs has been found to depend only upon the tank construction type, rim seal system type and seal fit. It does not depend upon ambient wind speed, V, as does the rim seal loss factor for EFRTs. Table 2 lists the IFRT rim seal loss factor for different rim seal systems with average-fitting seals.

The rim seal loss factor for EFRTs found in Table 1 may be compared with those for IFRTs found in Table 2. For the same rim seal type, the rim seal loss factor is generally less for an IFRT. This is most evident for primary-only rim seals, where the ambient wind plays a significant role in evaporative loss from EFRT rim seals.

5.3 Roof Fitting Loss Factor

The roof fitting loss factor, F_F, for EFRTs has been found to depend upon roof fitting type, roof fitting construction details, and ambient wind speed, V. Table 3 lists the EFRT roof fitting loss factor for typical roof fitting construction details at 5, 10 and 15 mi/hr wind speeds.

The roof fitting loss factor, F_F, for IFRTs has been found to depend upon only the roof fitting type and roof fitting construction details. It does not depend upon the ambient wind speed, V, as does the roof fitting loss factor for

EFRTs. Table 4 lists the IFRT roof fitting loss factor for typical roof fitting construction details.

The roof fitting loss factor for EFRTs found in Table 3 may be compared with those for IFRTs found in Table 4. For the same roof fitting type, the roof fitting loss factor is generally less for IFRTs. This is most evident for the roof fitting loss factor of a slotted guide-pole/sample well.

5.4 Roof Seam Loss Factor

The roof seam loss factor, F_D, accounts for the evaporative loss that occurs from seams on IFRT floating roofs and may be calculated from Equation 5:

$$F_D = K_D \, S_D \, D^2 \qquad (5)$$

Since the roof seam loss factor, F_D, is proportional to the square of the tank diameter, D, the evaporative loss contribution from the roof seams can be significant for large diameter tanks.

The roof seam loss factor, K_D, is 0 lb-mole/ft yr for welded floating-roof seams and 0.34 lb-mole/ft yr for bolted (i.e. mechanically joined) floating-roof seams.

The floating roof seam length factor, S_D, depends upon the floating roof construction type. A value of 0.20 ft/ft^2 can be used for typical floating roof construction.

5.5 Product Factor

The product factor, K_C, accounts for the effect of different types of liquid stocks on evaporative loss from EFRTs or IFRTs during tank working. Product factors have been developed for the following types of stocks:

STOCK TYPE	K_C (dimensionless)
Crude Oils	0.40
Refined Petroleum Stocks	1.00
Single-Component Petrochemical Stocks	1.00

5.6 Stock Clingage Factor

The stock clingage factor, C, accounts for the amount of stock that clings to the inside surface of the tank shell and to the surface of any fixed roof support columns when stock is withdrawn from the tank. Table 5 lists the clingage factor for different stock types and surface conditions.

6.0 FRT LOSS CALCULATION METHOD

API Publication 2518 [2] was recently updated and the Second Edition will be issued in the Fall of 1991. This Second Edition involves changes primarily to the standing storage loss calculation method.

The First Edition of API Publication 2518 was issued in 1962 and used a correlation for calculating the standing storage loss. This correlation was developed from evaporative loss data for FRTs storing gasoline and crude oils with a vapor pressure in the range from 1.5 to 8.8 psia.

Stocks with a vapor pressure over 1.5 psia are not now typically stored in FRTs. It was found that the standing storage loss correlation in the First Edition significantly overestimated the evaporative loss for stocks with a vapor pressure below 1.5 psia.

To update the First Edition of API Publication 2518, the API sponsored both a field tank test program to measure standing storage losses with low vapor pressure stocks and an analytical study to better understand the breathing loss mechanism. The Second Edition now uses a theoretically derived standing storage loss equation that has been confirmed by the available test data. This new standing storage loss equation applies to nonboiling stocks, including low vapor pressure stocks.

6.1 FRT Loss Equations

Total Loss

The total loss, L_T, is the sum of the working loss, L_W, and the standing storage loss, L_S, as shown in Equation 6:

$$\boxed{L_T = L_W + L_S} \qquad (6)$$

Working Loss

The working loss, L_W, may be calculated from Equation 7:

$$L_W = 0.0010\ M_V\ P_{VA}\ Q\ K_N\ K_P \tag{7}$$

Standing Storage Loss

The standing storage loss, L_S, may be calculated from Equation 8:

$$L_S = 365\ (V_V\ K_E)(W_V\ K_S) \tag{8}$$

Equation 8 involves the product of two terms:

o First Term, (V_V K_E)

The first term is the product of the tank vapor space volume, V_V, and the vapor space expansion factor, K_E. This term represents the volume of gas expelled from the tank vapor space during a single daily thermal breathing cycle.

o Second Term, (W_V K_S)

The second term is the product of the stock vapor density, W_V, and the vented vapor saturation factor, K_S. This term represents the average stock vapor density in the gas expelled during the daily thermal breathing cycle.

The tank vapor space volume, V_V, may be calculated from Equation 9:

$$V_V = \frac{\pi}{4} D^2 H_{VO} \tag{9}$$

The stock vapor density, W_V, may be calculated from Equation 10:

$$W_V = \frac{M_V P_{VA}}{R T_{LA}} \tag{10}$$

The vapor space expansion factor, K_E, is discussed below in Section 6.2 and the vented vapor saturation factor, K_S, is discussed in Section 6.3.

6.2 Vapor Space Expansion Factor

The vented vapor expansion factor, K_E, is defined as the fraction of the tank vapor space gas that is expelled during a daily thermal breathing cycle. This factor typically varies from 0.02 to 0.08, depending upon conditions, and may be calculated from Equation 11:

$$K_E = \left(\frac{\Delta T_V}{T_{LA}}\right) + \left(\frac{\Delta P_V}{P_A - P_{VA}}\right) - \left(\frac{\Delta P_B}{P_A - P_{VA}}\right) \tag{11}$$

Equation 11 consists of three separate terms:

- First Term, $(\Delta T_V/T_{LA})$

  The first term represents the vapor space gas expansion that is due to the daily ambient heating of the vapor space gas.

- Second Term, $(\Delta P_V/(P_A-P_{VA}))$

  The second term represents the vapor space gas expansion that is due to the additional stock that evaporates into the vapor space as a result of the daily ambient heating of the stock liquid surface.

- Third Term, $(\Delta P_B/(P_A-P_{VA}))$

  The third term is subtracted from the first two terms. This term represents a reduction of the total vapor space gas expansion that is due to the gas compression caused by an increase in tank gage pressure between the vacuum and pressure settings of the pressure/vacuum vent.

In order to calculate the vapor space expansion factor, K_E, from Equation 11, it is first necessary to determine certain temperature parameters, including:

- Daily average stock liquid surface temperature, T_{LA}.
- Daily vapor temperature range, ΔT_V.
- Daily maximum liquid surface temperature, T_{LX}.
- Daily minimum liquid surface temperature, T_{LN}.

These parameters may be calculated from Equations 12 through 15, respectively:

$$T_{LA} = 0.44\ T_{AA} + 0.56\ T_B + 0.0079\ \alpha\ I \qquad (12)$$

$$\Delta T_V = 0.72\ \Delta T_A + 0.028\ \alpha\ I \qquad (13)$$

$$T_{LX} = T_{LA} + 0.25\ \Delta T_V \qquad (14)$$

$$T_{LN} = T_{LA} - 0.25\ \Delta T_V \qquad (15)$$

If the liquid bulk temperature, T_B, is not available from tank operating records, it may be estimated from Equation 16:

$$T_B = T_{AA} + 6\ \alpha - 1 \qquad (16)$$

In order to calculate the temperatures in Equations 12, 13 and 16, it is necessary to know the following meteorological information for the tank site:

- Daily average ambient temperature, T_{AA}.
- Daily ambient temperature range, ΔT_A.
- Daily total solar insolation (or incident-solar-radiation) on a horizontal surface, I.

This information is generally available from the records of the nearest weather station. Note that the daily average ambient wind speed, V, is not used in the evaporative loss calculation method for a FRT.

The tank paint solar absorptance, α, is required in Equations 12, 13 and 16. This has been found to be an important parameter in standing storage evaporative loss from FRTs. The paint solar absorptance is the fraction of solar insolation absorbed by the tank's outside surface. The tank paint solar absorptance is a function of the tank paint color, paint shade or type, and paint condition. It varies between 0 and 1, with the more reflective paints having lower values of solar absorptance. Table 6 lists the solar absorptance for selected tank paints.

After the temperature parameters are calculated from Equations 12 through 16, it is then necessary to determining the following stock vapor pressure parameters:

- Stock vapor pressure at the daily maximum stock liquid surface temperature, P_{LX}.
- Stock vapor pressure at the daily average stock liquid surface temperature, P_{LA}.

- Stock vapor pressure at the daily minimum stock liquid surface temperature, P_{LN}.
- Stock daily vapor pressure range, ΔP_V.

These parameters may be calculated from Equations 17 through 20, respectively:

$$P_{VX} = \exp\left[A - (B/T_{LX})\right] \tag{17}$$

$$P_{VA} = \exp\left[A - (B/T_{LA})\right] \tag{18}$$

$$P_{VN} = \exp\left[A - (B/T_{LN})\right] \tag{19}$$

$$\Delta P_V = P_{VX} - P_{VN} \tag{20}$$

The vapor pressure equation constants A and B depend upon the stock type. Tables 6 and 7 in Reference [2] list these constants for selected petroleum liquid stocks and petrochemical stocks, respectively.

6.3 Vented Vapor Saturation Factor

The vented vapor saturation factor, K_S, accounts for the degree of stock vapor saturation in the vented vapor. This factor varies between 0 and 1 and may be calculated from Equation 21:

$$K_S = \frac{1}{1 + 0.053\, P_{VA}\, H_{VO}} \tag{21}$$

Figure 33 shows the dependency of the vented vapor saturation factor, K_S, on the parameters P_{VA} and H_{VO}. As the stock vapor pressure, P_{VA}, or tank vapor space outage, H_{VO}, increase, the vented vapor saturation factor, K_S, decreases (i.e. the degree of stock vapor saturation in the vented vapor is less).

The degree of saturation in the vented vapor is related to the mass transfer rate limitations between the stock liquid surface and the area below the pressure-vacuum vent. As the vapor space outage, H_{VO}, increases, the distance that the stock vapor must travel from the liquid surface to the vent is lengthened. This lengthened distance decreases the mass transfer rate and thus reduces the degree of saturation in the vented gas. As the stock vapor pressure, P_{VA}, increases, the amount of stock vapor lost in each daily thermal breathing cycle increases. This higher vapor pressure requires a higher rate of evaporation from the liquid surface to replenish the stock vapor that is lost. Mass transfer rate limitations, however, restrict the ability of the stock to replenish the vented vapor and reduce the degree of saturation in the vented gas.

6.4 Working Loss Turnover Factor

The working loss turnover factor, K_N, is used to account for the non-saturation conditions that occur in the vented vapor for tanks where the annual net throughput, Q, is large, resulting in frequent tank turnovers (i.e. greater than 36 turnovers per year). The working loss turnover factor may be calculated from Equations 22 and 23:

$$K_N = \frac{180 + N}{6\ N} \qquad \text{(for } N > 36\text{)} \qquad (22)$$

$$K_N = 1 \qquad \text{(for } N \leq 36\text{)} \qquad (23)$$

Figure 34 shows the dependency of the working loss turnover factor, K_N, on the stock turnover rate, N. For example, at N = 100 (i.e. 100 turnovers per year) the working loss turnover factor is $K_N = 0.467$.

6.5 Working Loss Product Factor

The working loss product factor, K_P, accounts for the effect of different types of liquid stocks on evaporative loss from a FRT during tank working. Product factors have been developed for the following types of stocks:

STOCK TYPE	K_P (dimensionless)
Crude Oils	0.75
Refined Petroleum Stocks	1.00
Single-Component Petrochemical Stocks	1.00

7.0 SAMPLE CALCULATIONS

To illustrate the use of the above evaporative loss estimation methods, they will be applied to a sample problem. Losses will be calculated for an EFRT and an IFRT storing a 1.5 psia crude oil.

Table 7 summarizes the assumed conditions for the sample problem. Loss calculations will be made for tank diameters of 50, 100, 150 and 200 feet. The loss calculations will be made for several different floating roof sealing systems to determine their relative effect on evaporative loss.

It should be cautioned that additional combinations of assumed tank conditions are possible, and the losses calculated for this sample problem are thus not an exhaustive comparison of loss control options. It should be noted that a complete evaluation of different loss control techniques and storage tank options must include both a loss analysis and cost evaluation. Also, the relative losses that result in this sample problem for crude oil may not apply to other stocks such as gasoline, petrochemicals, etc.

Table 8 summarizes the results of the loss calculations, where the loss contribution of each loss source is listed.

Table 9 summarizes the total losses for each combination of assumed tank conditions.

Several interesting trends may be observed from Tables 8 and 9.

- A liquid-mounted resilient-filled primary seal has significantly lower evaporative loss than a vapor-mounted resilient-filled primary seal on an EFRT.

- A liquid-mounted resilient-filled primary seal with a rim-mounted secondary seal is essentially equivalent in evaporative loss to a mechanical-shoe primary seal with a rim-mounted secondary seal on an EFRT.

- The use of a rim-mounted secondary seal on an IFRT is not as effective in reducing the rim seal loss as it is on an EFRT. However, it does still result in some reduction in evaporative loss on an IFRT.

- The roof fitting loss and the roof seam loss can significantly exceed the rim seal loss on tanks equipped with secondary seals.

- The roof seam loss is significant on large diameter IFRTs.

- The roof fitting loss from an IFRT can in some cases exceed the roof fitting loss from an EFRT if a column-supported fixed roof is used on the IFRT. This is due to the additional evaporative loss contribution from the column wells on an IFRT.

8.0 CONCLUSIONS

There is a continuing need to accurately calculate evaporative losses from aboveground storage tanks. Knowing these evaporative losses is important for determining both product losses and atmospheric emissions. In the U.S., there is a continuing emphasis on lower atmospheric emissions from storage tanks.

This year (1991) the American Petroleum Institute (API) completed the cycle of updating all three of its core evaporative loss publications that deal with aboveground storage tanks. These publications deal with evaporative losses from External Floating-Roof Tanks (EFRTs), Internal Floating-Roof Tanks (IFRTs) and Fixed-Roof Tanks (FRTs). The updated API evaporative loss publications are the result of an extensive API-sponsored laboratory and field testing program that included analytical developments to model storage tank evaporative loss processes.

These revised API publications now permit loss calculations to be made with greater detail and accuracy for different alternative control options. As a result, storage tank manufacturers, owners and operators can better focus development efforts on achieving further reductions in evaporative loss.

As a result of the API-sponsored testing programs, a number of specific conclusions can be made about evaporative losses from EFRTs, IFRTs and FRTs:

External Floating Roof Tank (EFRT)

- Rim Seal System Type
  Losses from an EFRT are a strong function of the type of rim seal system.

- Primary Seal Types
  Vapor-mounted resilient-filled primary seals have significantly higher evaporative loss than liquid-mounted resilient-filled primary seals or mechanical-shoe primary seals.

- Primary Seal Gaps

  Small primary seal gaps (e.g. 1 in^2/ft dia.) do not result in a significant increase in evaporative loss from liquid-mounted resilient-filled primary seals or mechanical-shoe primary seals. Losses from vapor-mounted resilient-filled primary seals, however, are more sensitive to small gaps.

- Secondary Seals

  Rim-mounted secondary seals are very effective in reducing evaporative loss.

  Shoe-mounted secondary seals are used only with mechanical-shoe primary seals. They are helpful in reducing losses from gaps between the tank shell and the shoe, but are not as effective as rim-mounted secondary seals since they cannot provide any control of losses coming from the primary seal fabric.

  Weather shields are helpful in reducing emissions, but are not as effective as rim-mounted secondary seals.

- Secondary Seal Gaps

  Small secondary seal gaps (e.g. 1 in^2/ft dia.) do not result in a significant increase in evaporative loss. Secondary seals are effective in reducing losses, even when the primary seal has large gaps (e.g. 3 in^2/ft dia.).

- Roof Fittings

  Evaporative loss from external floating roof fittings can be a significant portion of the total loss, especially when a rim-mounted secondary seal is used to reduce the rim seal loss.

  Evaporative loss from a slotted guide-pole/sample well is significantly larger than that from other external floating roof fittings.

- Wind Speed

  Evaporative losses from rim seals and roof fittings are a strong function of the average wind speed. For vapor-mounted primary seals, the higher measured losses were affected by the wind-induced loss mechanism of circumferential air flow in the rim vapor space.

- Vapor Pressure

  The theoretically derived [8] vapor pressure function, P^*, adequately correlated the variable vapor pressure test data.

Internal Floating-Roof Tank (IFRT)

- Floating Roof Type

  The major evaporative loss-related difference between floating roof types is the method of floating roof seam construction (i.e. "welded" versus "bolted" seams), not the amount of contact that the floating roof has with the stock liquid surface.

- Primary Seals

  Evaporative losses from a liquid-mounted primary seal are approximately 55% lower than the evaporative losses from a vapor-mounted primary seal.

- Primary Seal Gaps

  Small primary seal gaps (e.g. 1 in^2/ft dia.) do not result in a significant increase in evaporative losses. Consistently tight fitting primary seals have only slightly lower evaporative losses than average fitting primary seals.

- Secondary Seals

  Rim-mounted secondary seals on an IFRT are effective in reducing evaporative losses, but not to the degree that they are when used on an EFRT. Evaporative losses from IFRT rim seal systems which includes a secondary seal are approximately 50% lower than evaporative losses from the primary seal only.

- Secondary Seal Gaps

  Small secondary seal gaps (e.g. 1 in^2/ft dia.) do not result in a significant increase in evaporative losses.

- Roof Fittings

  Evaporative losses from IFRT floating roof fittings can be a significant portion of the total evaporative losses, especially when a rim-mounted secondary seal is used to reduce the rim seal loss.

  Evaporative losses from the roof fittings on an IFRT with a column-supported fixed roof can exceed the evaporative losses from the roof fittings on an EFRT due to the loss contribution of the column wells on the IFRT.

  Evaporative losses from a ladder well or a slotted guide-pole/sample well are larger than the evaporative losses from the other types of roof fittings.

- Wind Speed

  The pilot tank test results demonstrated that evaporative losses from the rim seal and roof fittings are not dependent upon the ambient wind speed.

- Product Type

  The product factor, K_C, was demonstrated to have a value of 1.0 for both single-component petrochemical stocks and refined multicomponent petroleum stocks.

- Vapor Pressure

  Evaporative loss data from single-component petrochemical stocks and multicomponent petroleum liquid stocks were found to be adequately correlated when using the theoretically derived [8] vapor pressure function, P^*.

Fixed Roof Tank (FRT)

- Tank Paint

  Tank paint with a low solar absorptance is effective in reducing the standing storage loss.

- Tank Insulation

  Insulation on the tank shell and roof is effective in reducing the standing storage loss. However, the current FRT loss calculation method [2] does not yet include provisions to account for the use of tank insulation.

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NOMENCLATURE

Symbol	Description	Units
A	constant in the vapor pressure equation	dimensionless
B	constant in the vapor pressure equation	^oR
C	clingage factor	bbl/1000 ft^2
D	tank diameter	ft
F_C	effective column diameter	ft
F_D	roof seam loss factor	lb-mole/yr
F_F	total roof fitting loss factor	lb-mole/yr
F_R	rim seal loss factor	lb-mole/ft yr
H_{VO}	vapor space outage (or equivalent height)	ft
I	daily total solar insolation on a horizontal surface	Btu/ft^2 day
K_C	product factor	dimensionless
K_D	roof seam loss factor	lb-mole/ft yr
K_E	vapor space expansion factor	dimensionless
K_P	working loss product factor	dimensionless
K_S	vented vapor saturation factor	dimensionless
K_N	working loss turnover factor	dimensionless
L_S	standing storage loss	lb/yr
L_T	total loss	lb/yr
L_W	working loss or withdrawal loss	lb/yr
M_V	stock vapor molecular weight	lb/lb-mole
N	stock turnover rate	turnovers/yr
N_C	number of columns	dimensionless
P	stock vapor pressure	psia
P^*	vapor pressure function	dimensionless
P_A	atmospheric pressure	psia
ΔP_B	breather vent pressure setting range	psi
P_{VA}	stock vapor pressure at the daily average liquid surface temperature	psia
P_{VN}	stock vapor pressure at the daily minimum liquid surface temperature	psia
P_{VX}	stock vapor pressure at the daily maximum liquid surface temperature	psia
ΔP_V	stock daily vapor pressure range	psi

NOMENCLATURE (Continued)

Symbol	Description	Units
Q	stock annual net throughput (associated with increasing the stock liquid level in the tank)	bbl/yr
R	ideal gas constant (10.731)	$\frac{\text{psia ft}^3}{\text{lb-mole } ^oR}$
S_D	roof seam length factor	ft/ft^2
T_{AA}	daily average ambient temperature	^oR
ΔT_A	daily ambient temperature range	^oR
T_B	liquid bulk temperature	^oR
T_{LA}	daily average liquid surface temperature	^oR
T_{LN}	daily minimum liquid surface temperature	^oR
T_{LX}	daily maximum liquid surface temperature	^oR
ΔT_V	daily vapor temperature range	^oR
t	time	days
V_V	tank vapor space volume	ft^3
W_L	stock liquid density	lb/gal
W_V	stock vapor density	lb/ft^3
	Greek Symbol Notation	
α	tank paint solar absorptance	dimensionless
	Unit Notation	
Btu	British thermal unit	
ft	feet	
hr	hour	
lb	pound mass	
lb-mole	pound mole	
mi	mile	
^oR	degrees Rankine	
^oF	degrees Fahrenheit	
	Conversion Relationships	
^oR	$= {}^oF + 459.67$	
psia	= psig + 14.696	

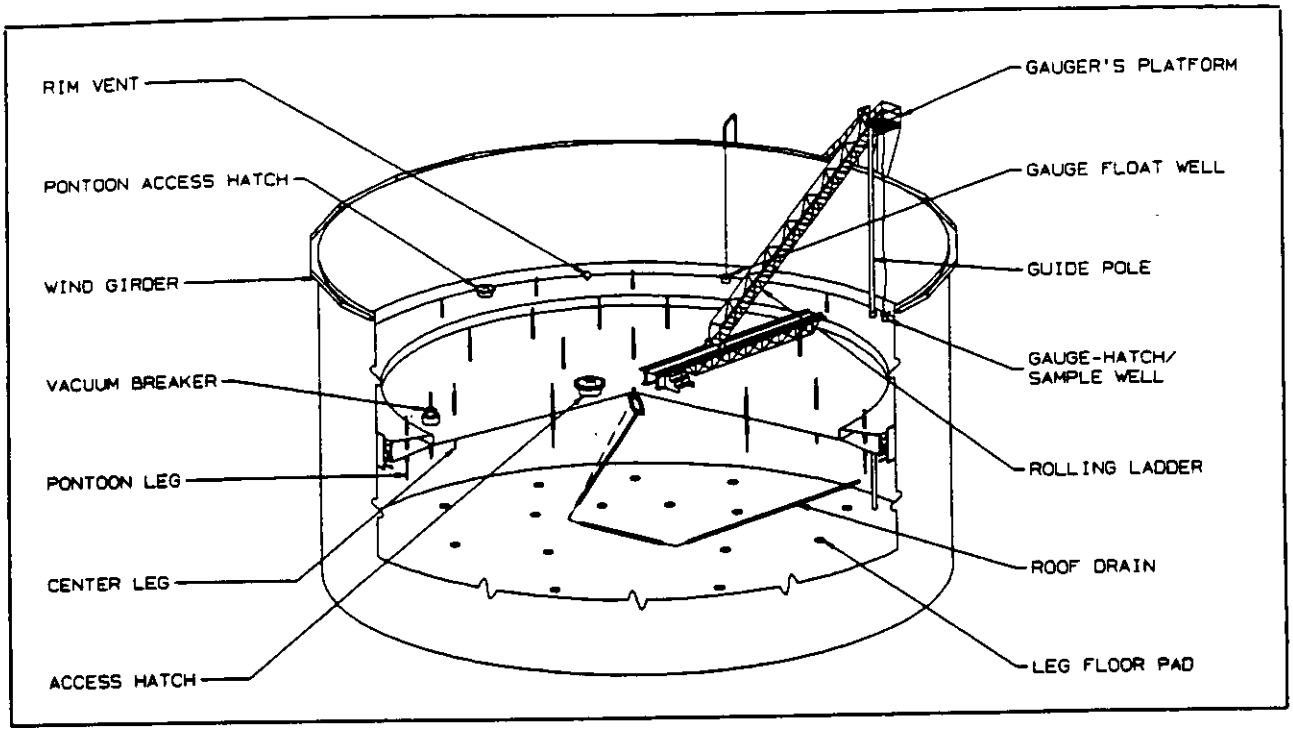


Figure 1 - Typical External Floating-Roof Tank (EFRT) With a Pontoon Floating Roof

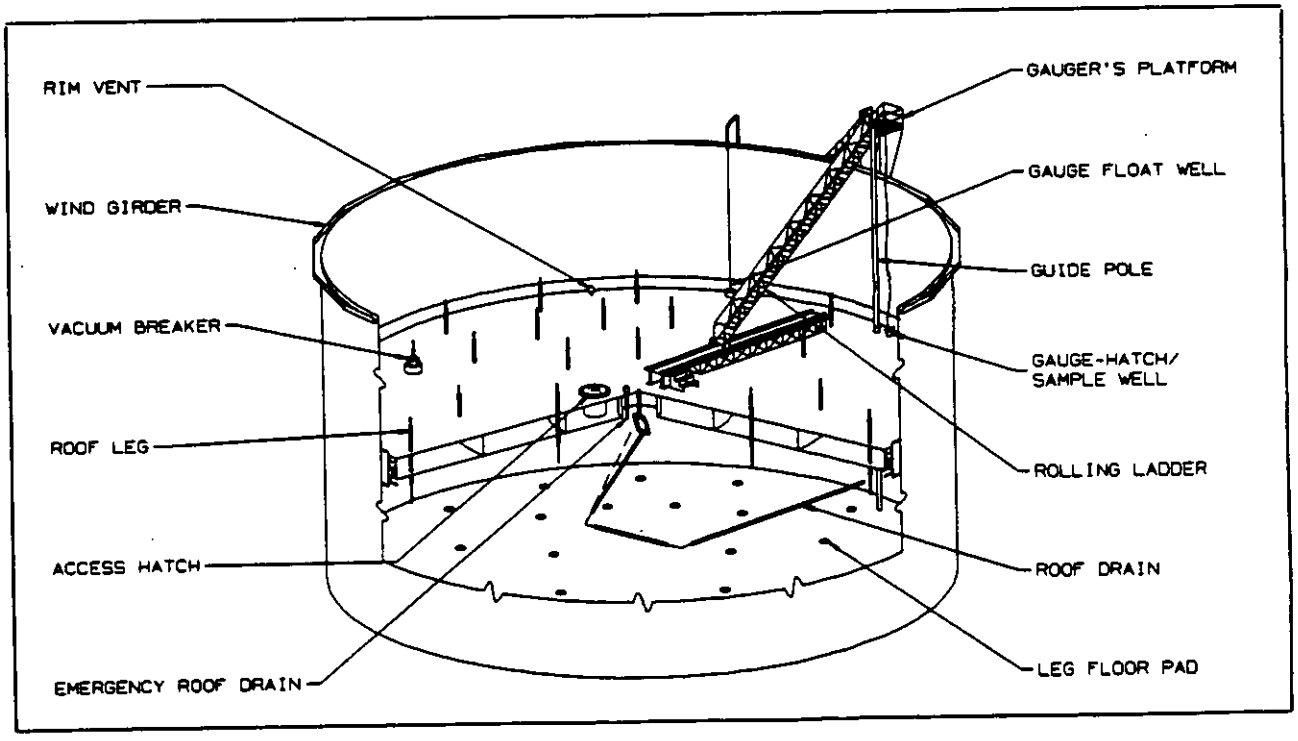


Figure 2 - Typical External Floating-Roof Tank (EFRT) With a Double-Deck Floating Roof

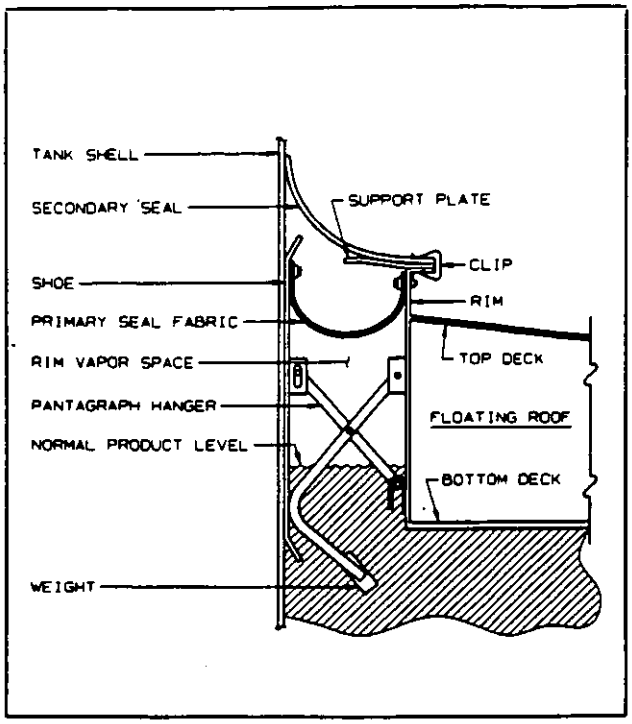


Figure 3 - Mechanical-Shoe Primary Seal With a Rim-Mounted Secondary Seal

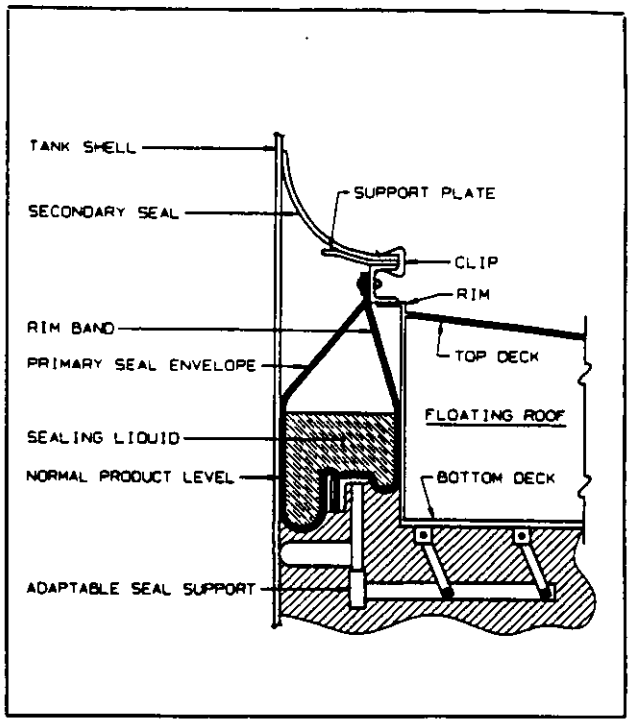


Figure 4 - Liquid-Mounted Resilient-Filled (Liquid-Filled) Primary Seal With a Rim-Mounted Secondary Seal

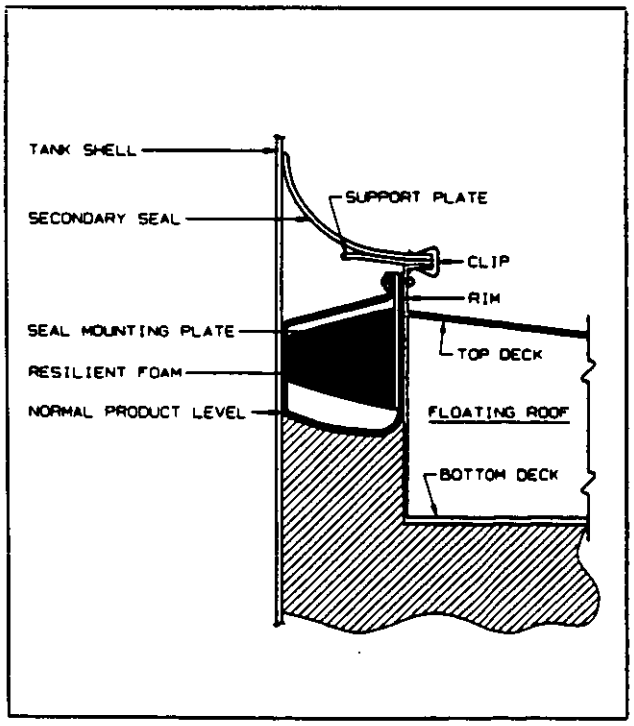


Figure 5 - Liquid-Mounted Resilient-Filled (Foam-Filled) Primary Seal With a Rim-Mounted Secondary Seal

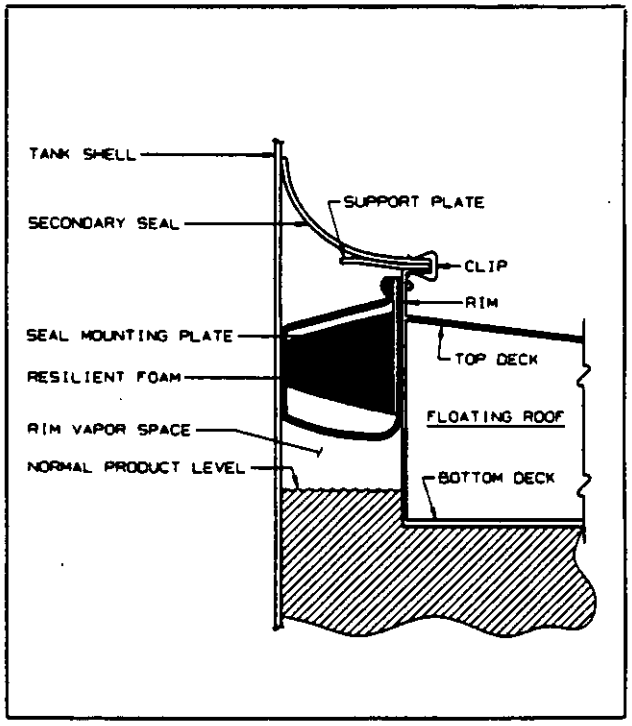


Figure 6 - Vapor-Mounted Resilient-Filled (Foam-Filled) Primary Seal With A Rim-Mounted Secondary Seal

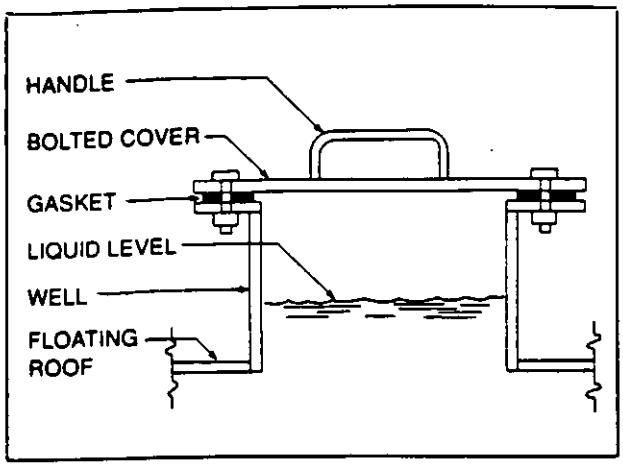


Figure 7 - Access Hatch

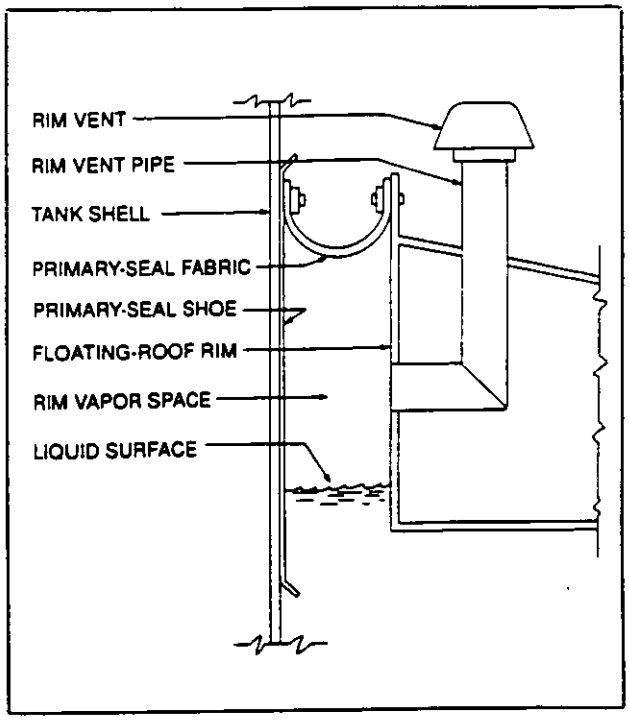


Figure 8 - Rim Vent

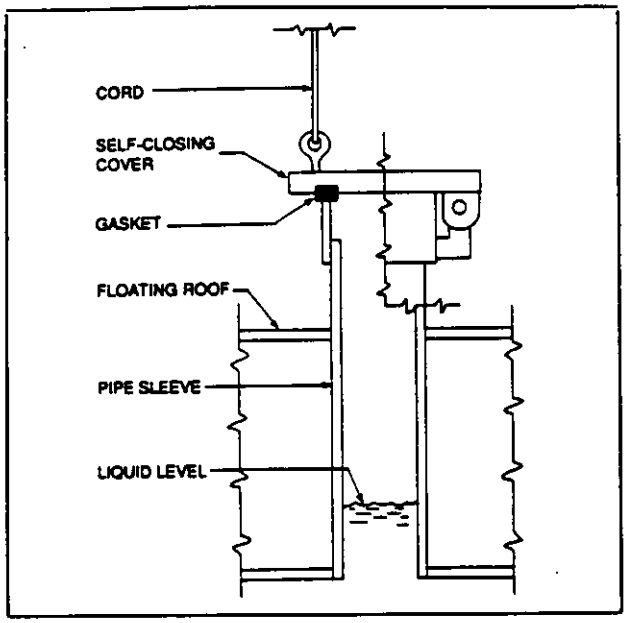
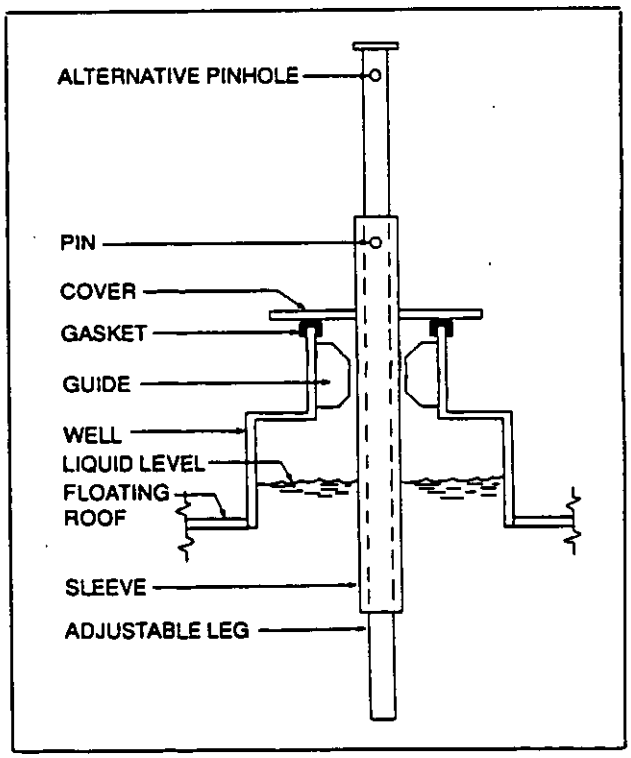


Figure 9 - Gauge-Hatch/Sample Well



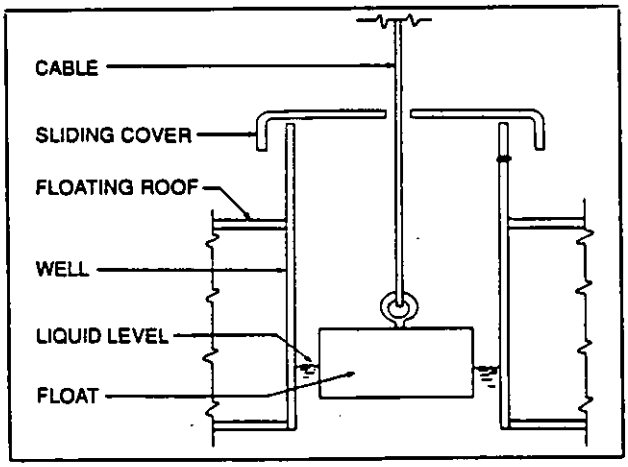


Figure 11 - Gauge-Float Well

Figure 10 - Vacuum Breaker

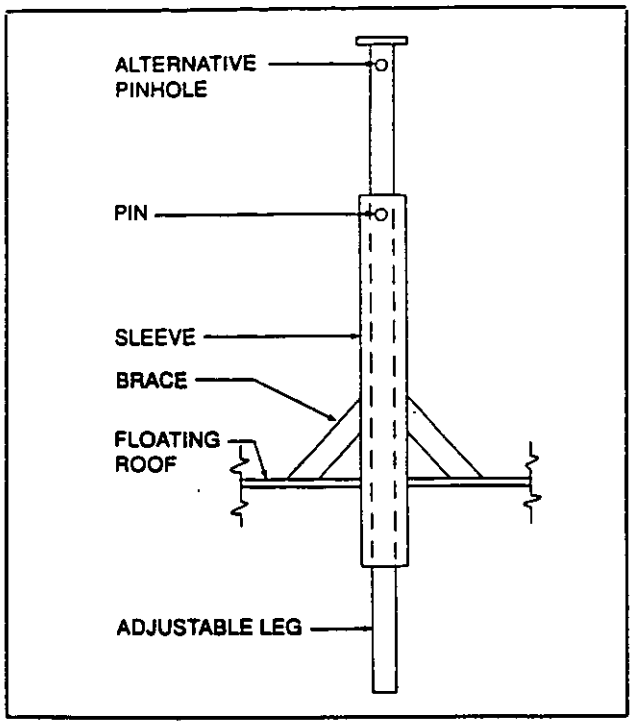


Figure 12 - Roof Leg

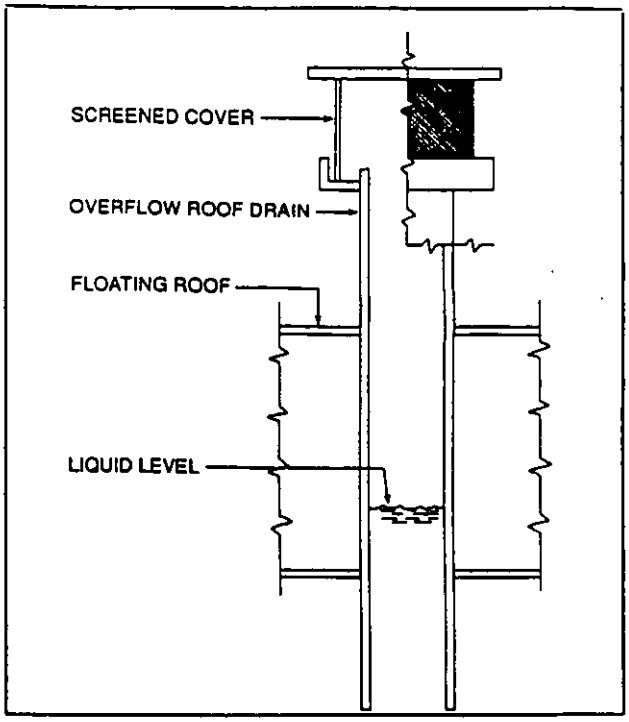


Figure 13 - Overflow Roof Drain

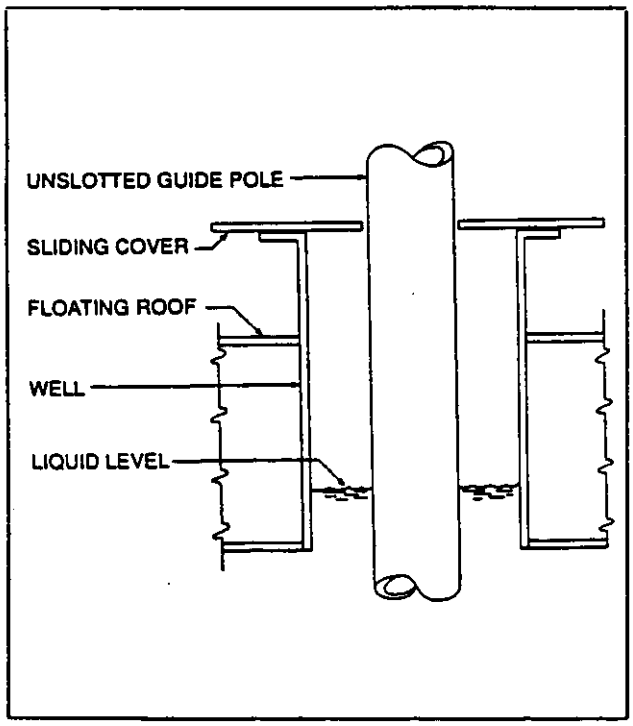


Figure 14 - Unslotted Guide-Pole Well

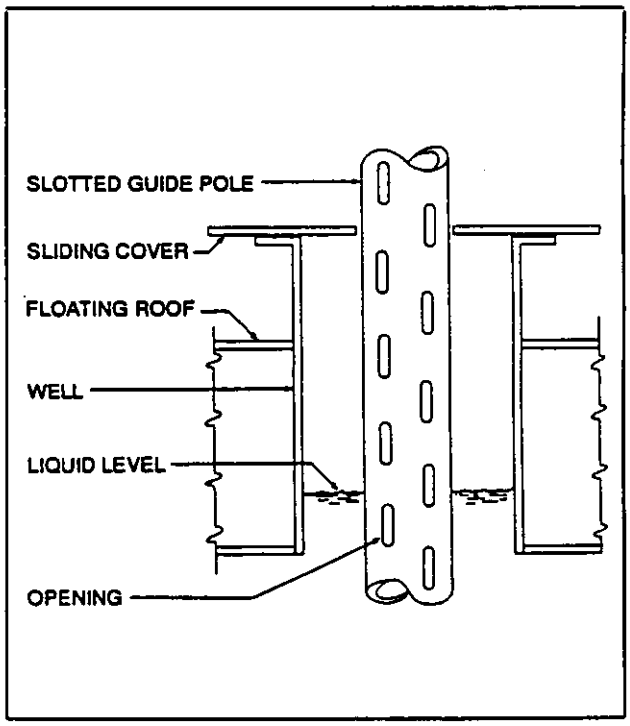


Figure 15 - Slotted Guide-Pole/Sample Well

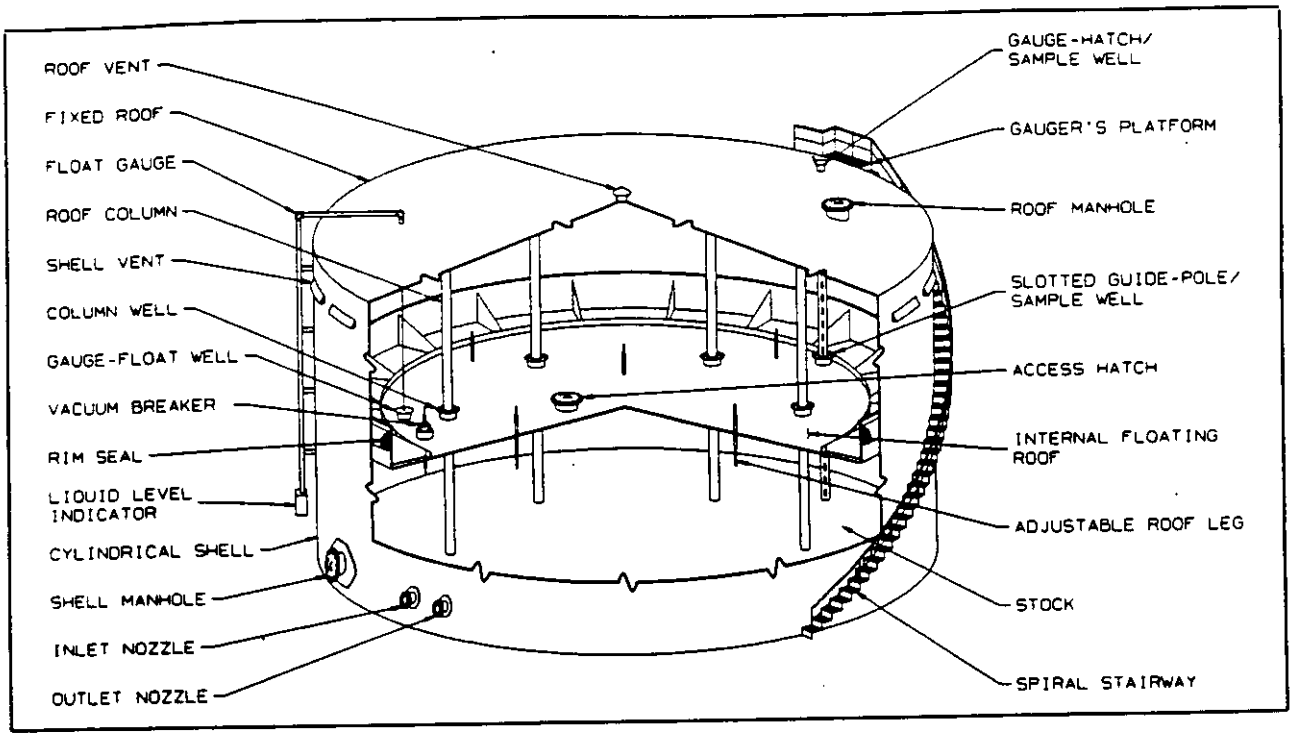


Figure 16 - Typical Internal Floating-Roof Tank (IFRT) With a Welded Floating Roof

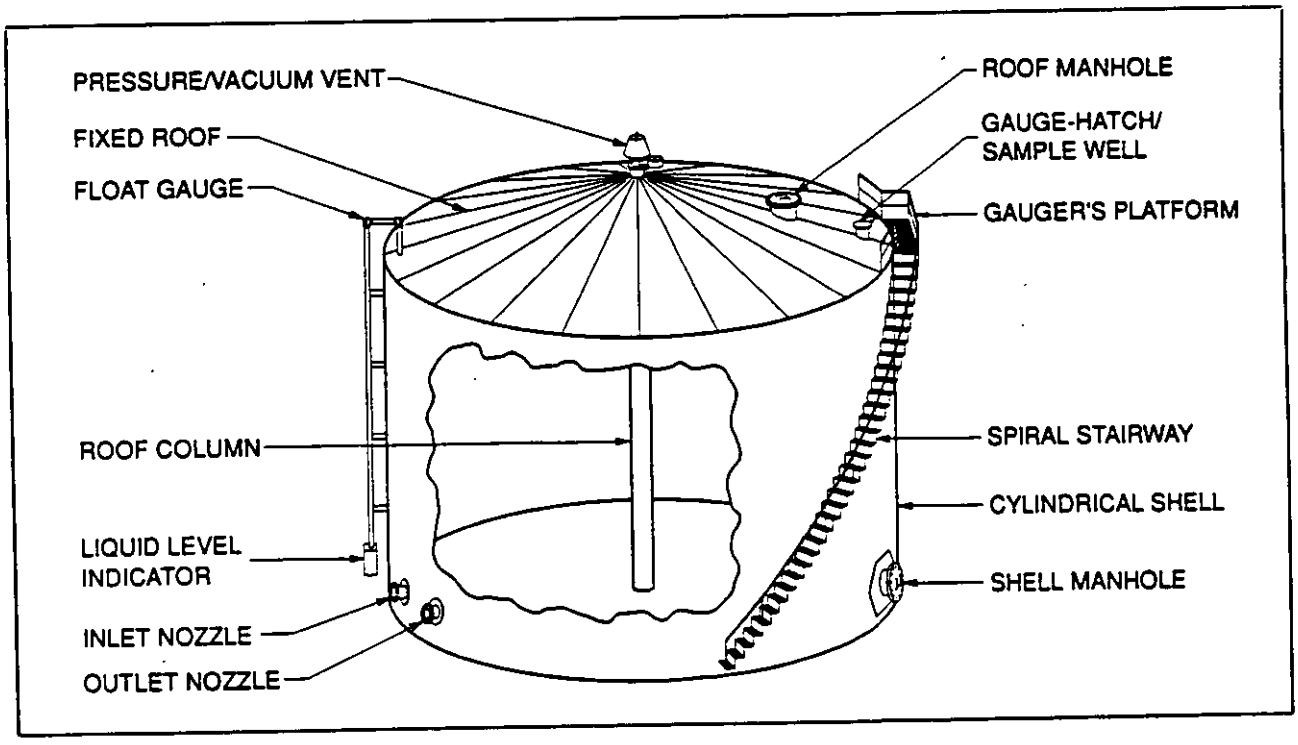


Figure 17 - Typical Fixed-Roof Tank (FRT)

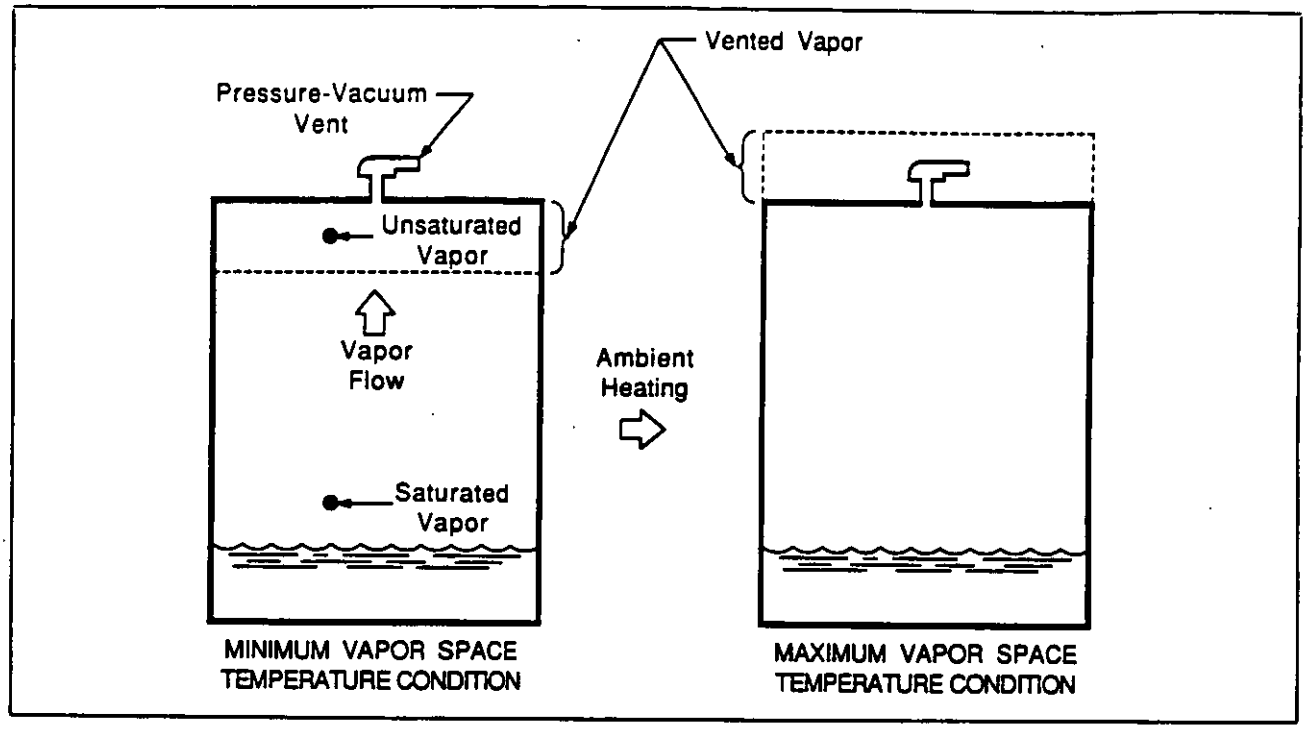


Figure 18 - Daily Ambient Heating-Related Breathing Loss Mechanism on a FRT

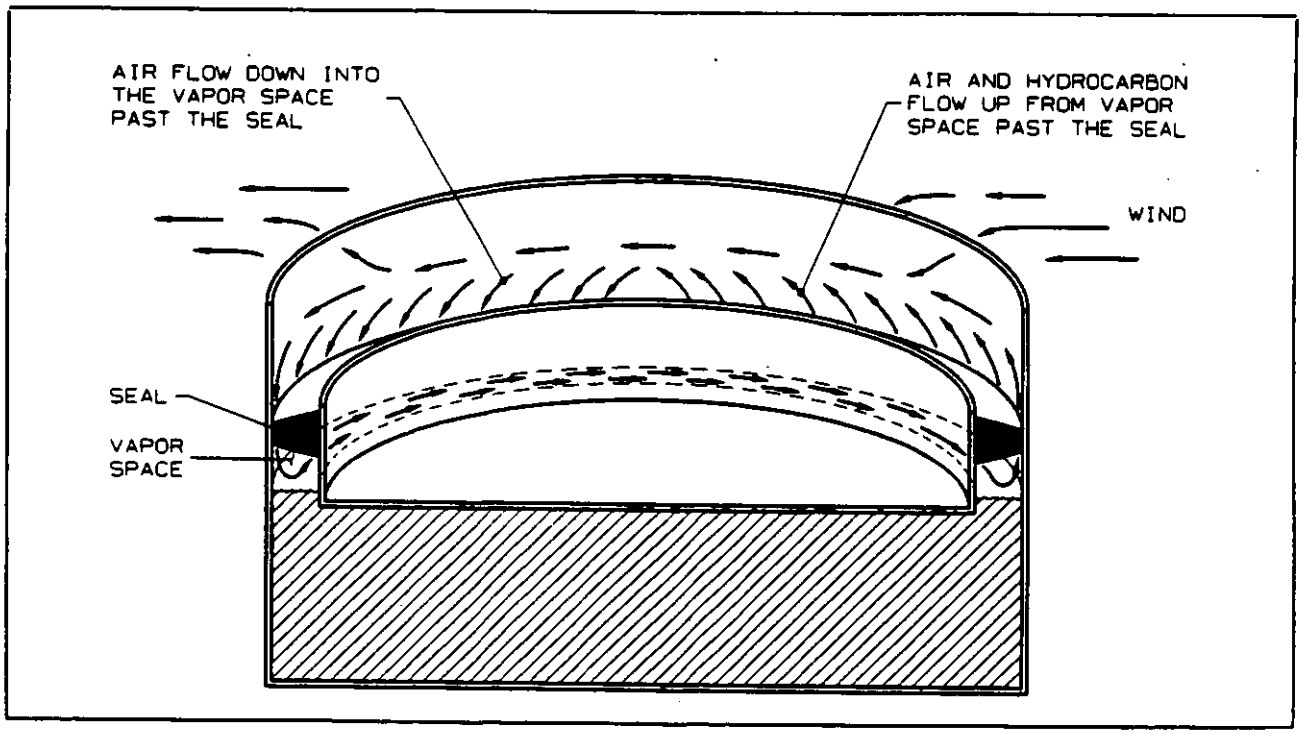


Figure 19 - Wind-Related Convection Loss Mechanism on an EFRT With a Vapor-Mounted Resilient-Filled Seal

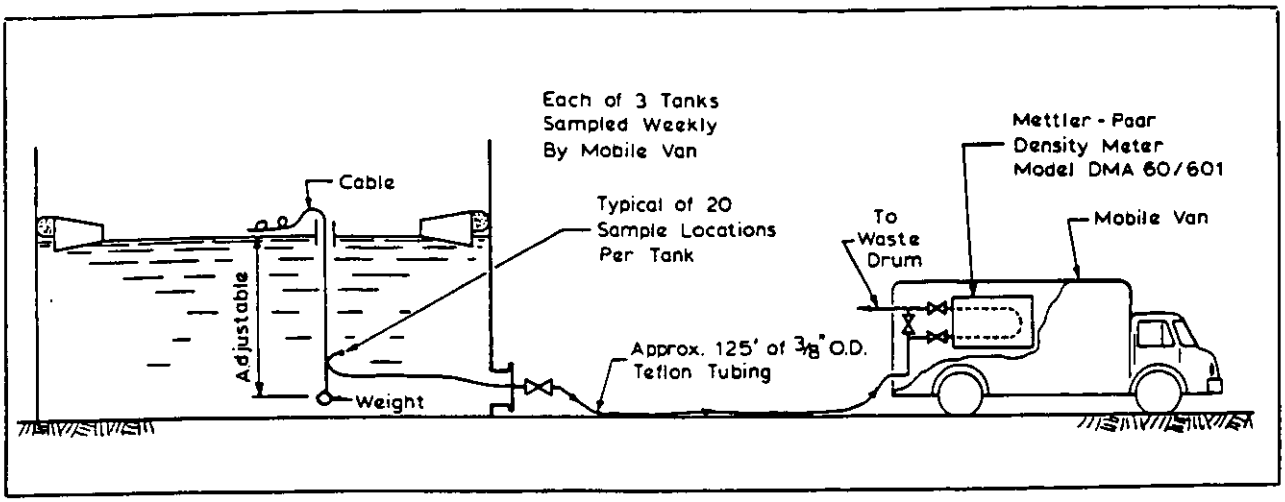


Figure 20 - Field Tank Tests Using the Stock Density Change Method

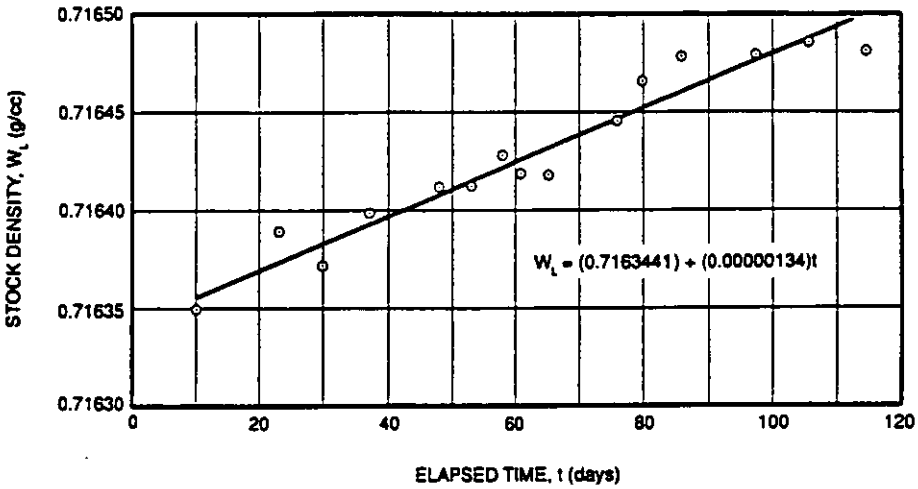


Figure 21 - Stock Density Change From Field Tank Test

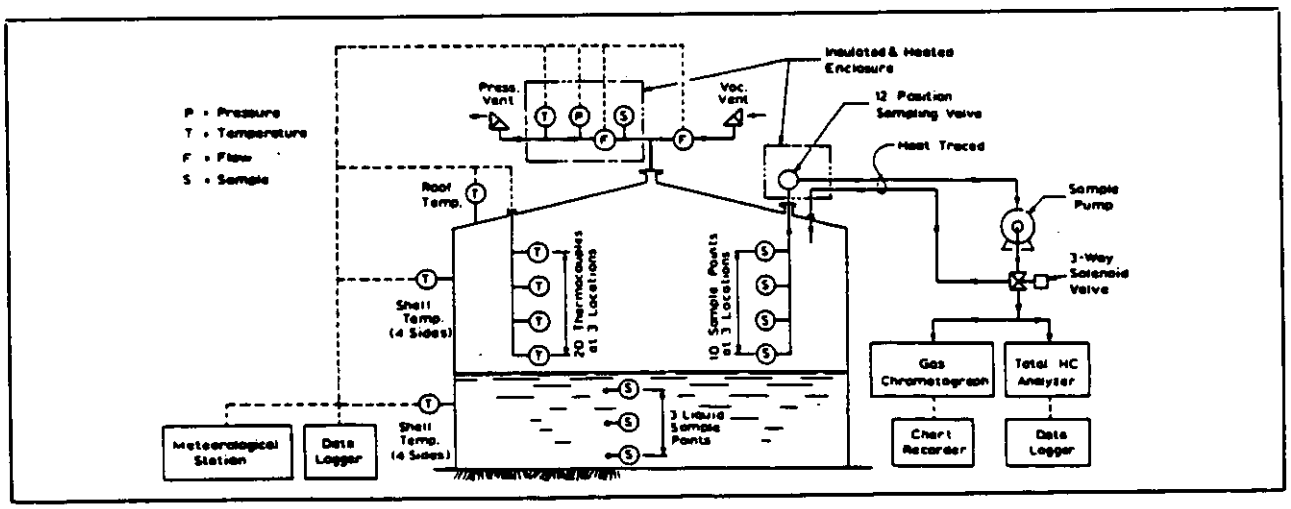


Figure 22 - Field Tank Tests Using the Vented Vapor Measurement Method

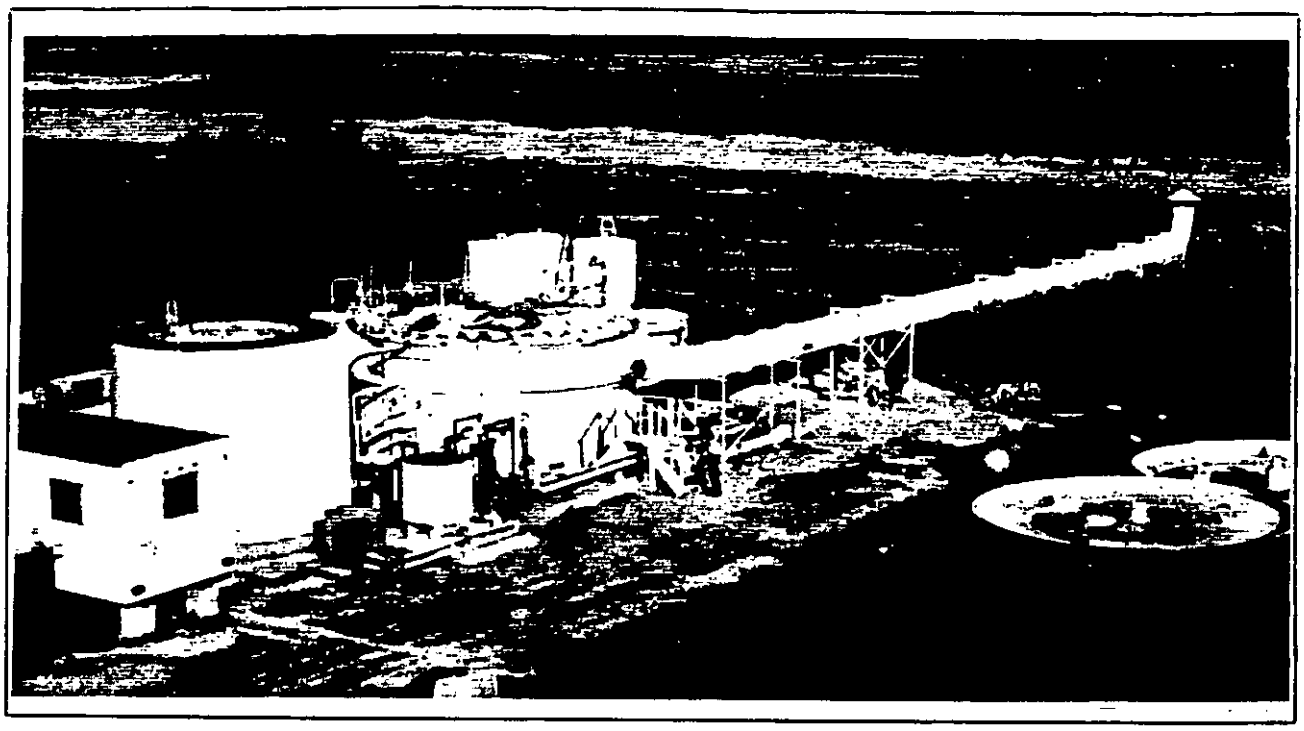


Figure 23 - Photograph of the Pilot Tank Test Facility

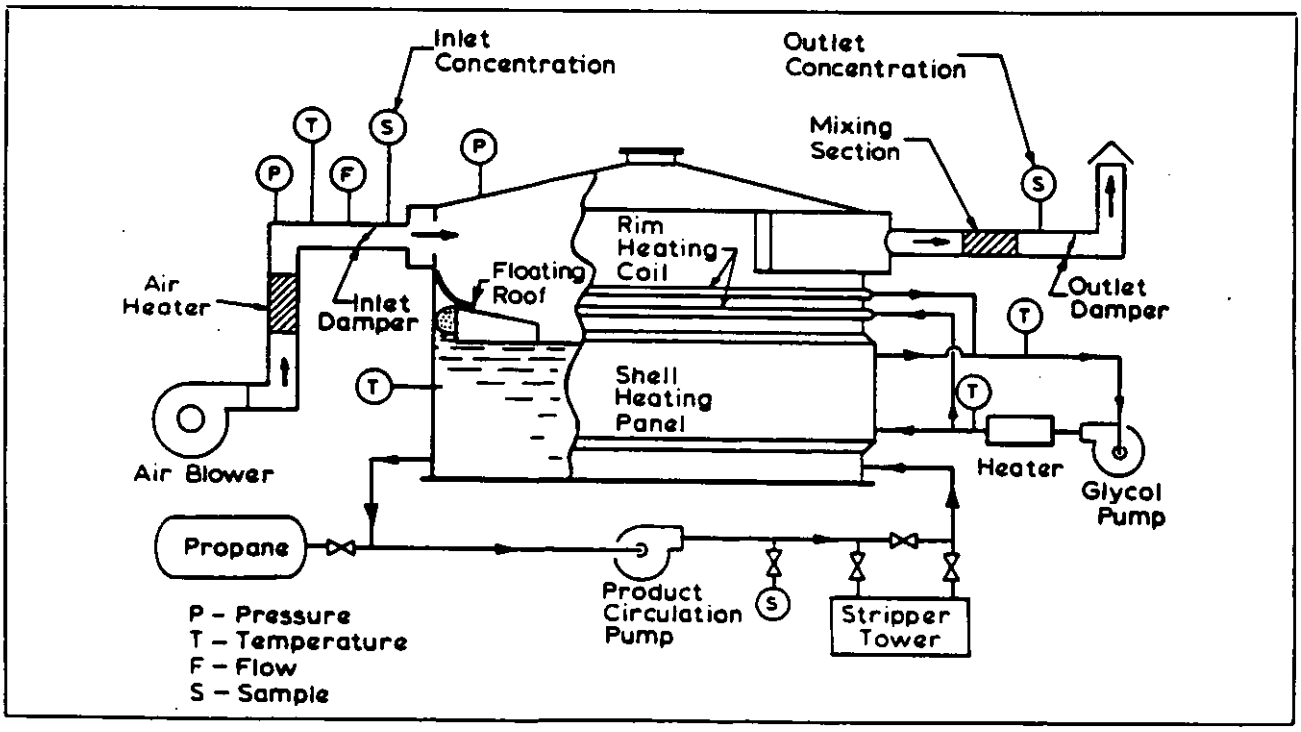


Figure 24 - Schematic Diagram of the Pilot Tank Test Facility

Figure 25 - Photograph of the Wind Tunnel Test Facility

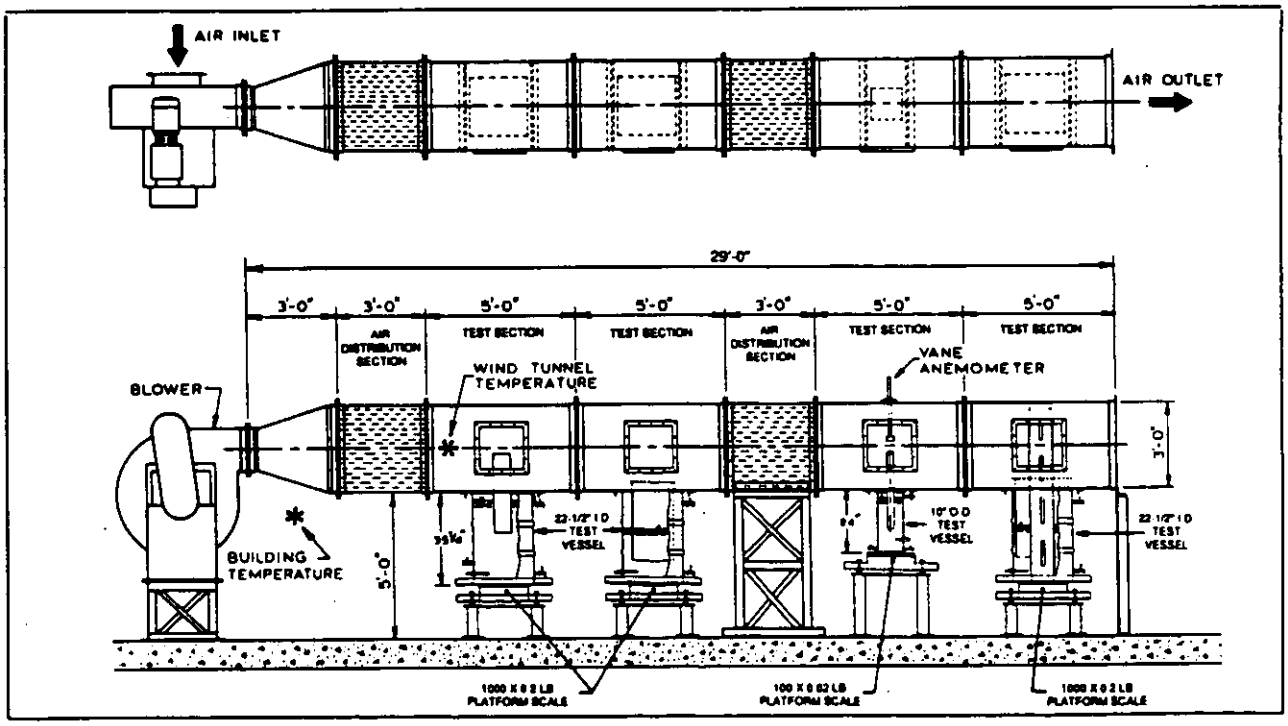


Figure 26 - Schematic Diagram of the Wind Tunnel Test Facility

Figure 27 - Photograph of the Stock Clingage Test Facility

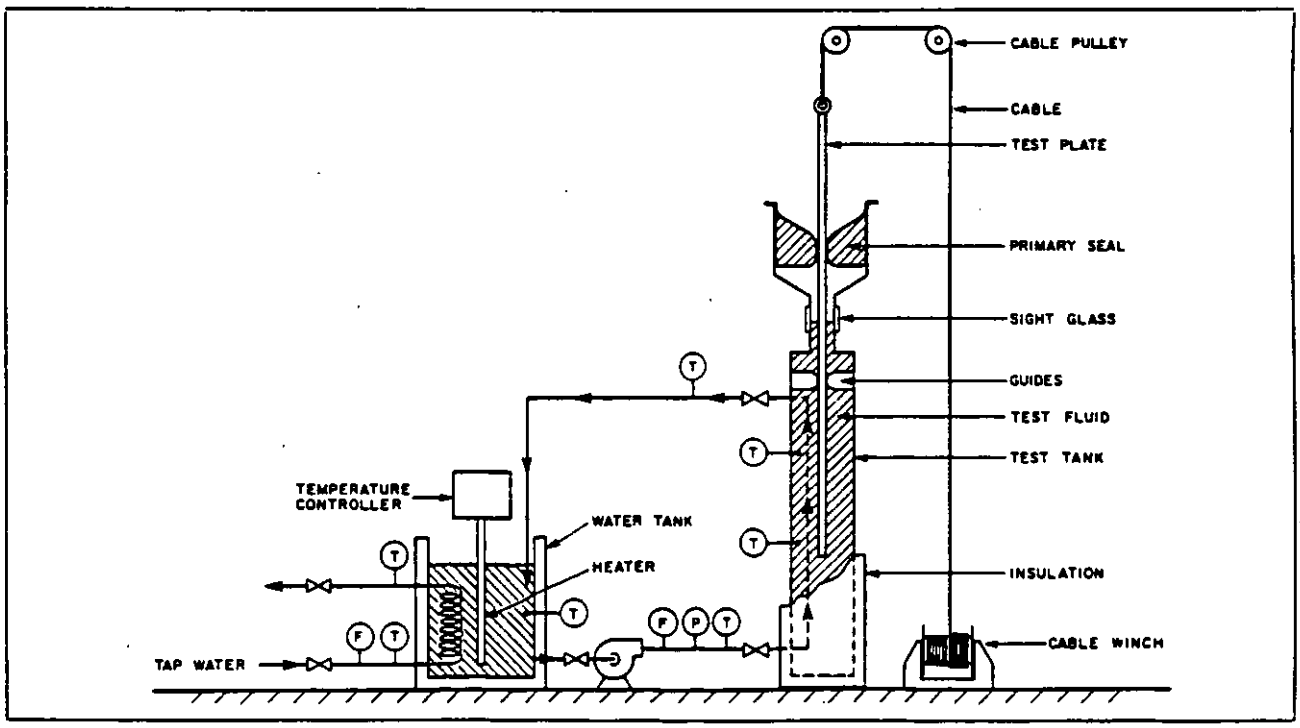


Figure 28 - Schematic Diagram of the Stock Clingage Test Facility

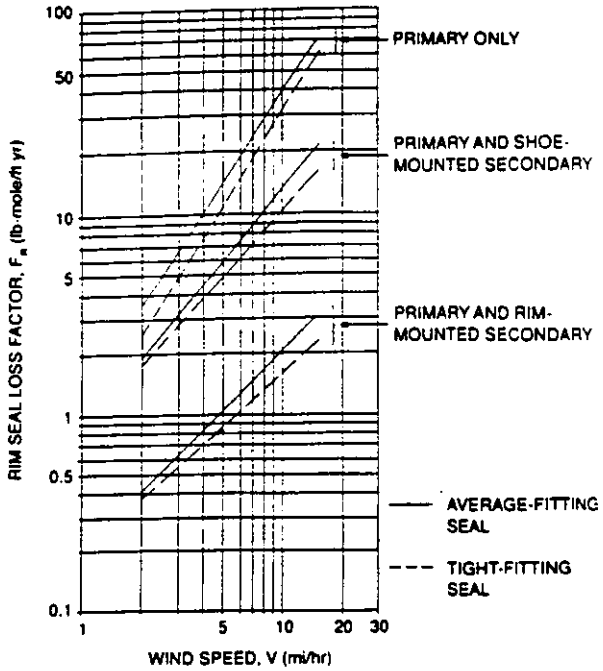


Figure 29- EFRT Rim Seal Loss Factor, F_R, Versus Wind Speed For a Welded Tank With a Mechanical-Shoe Seal

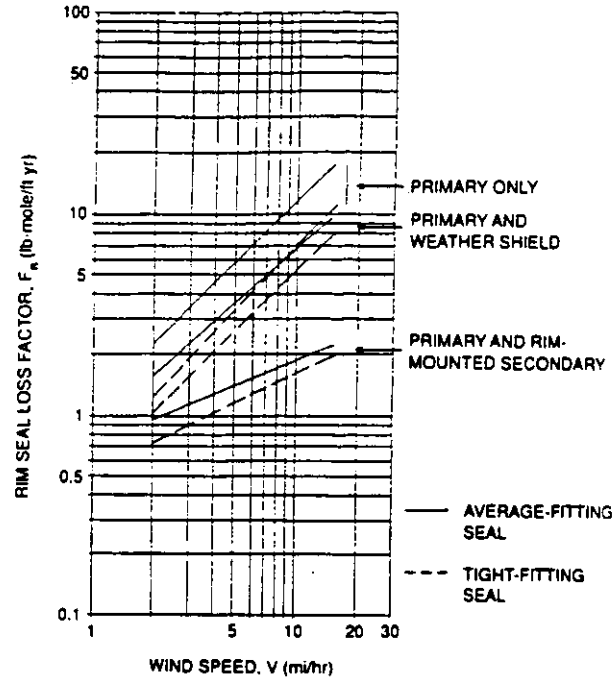


Figure 30- EFRT Rim Seal Loss Factor, F_R, Versus Wind Speed For a Welded Tank With a Liquid-Mounted Resilient-Filled Seal

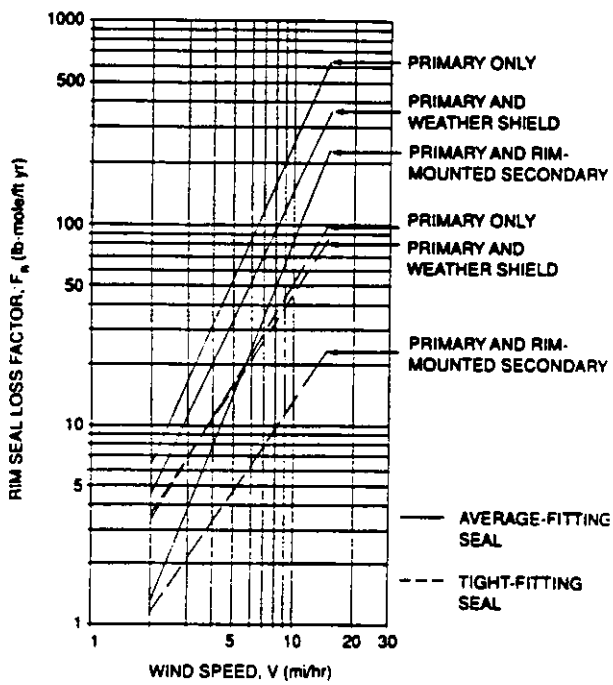


Figure 31- EFRT Rim Seal Loss Factor, F_R, Versus Wind Speed For a Welded Tank With a Vapor-Mounted Resilient-Filled Seal

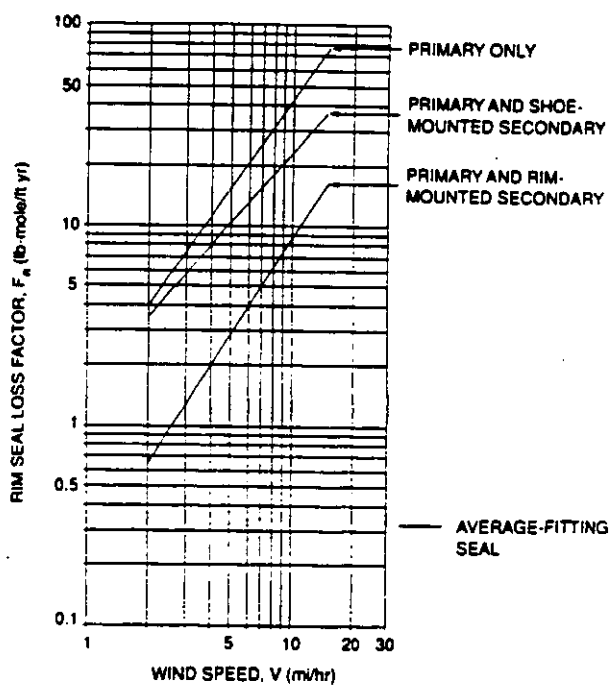


Figure 32- EFRT Rim Seal Loss Factor, F_R, Versus Wind Speed For a Riveted Tank With A Mechanical-Shoe Seal

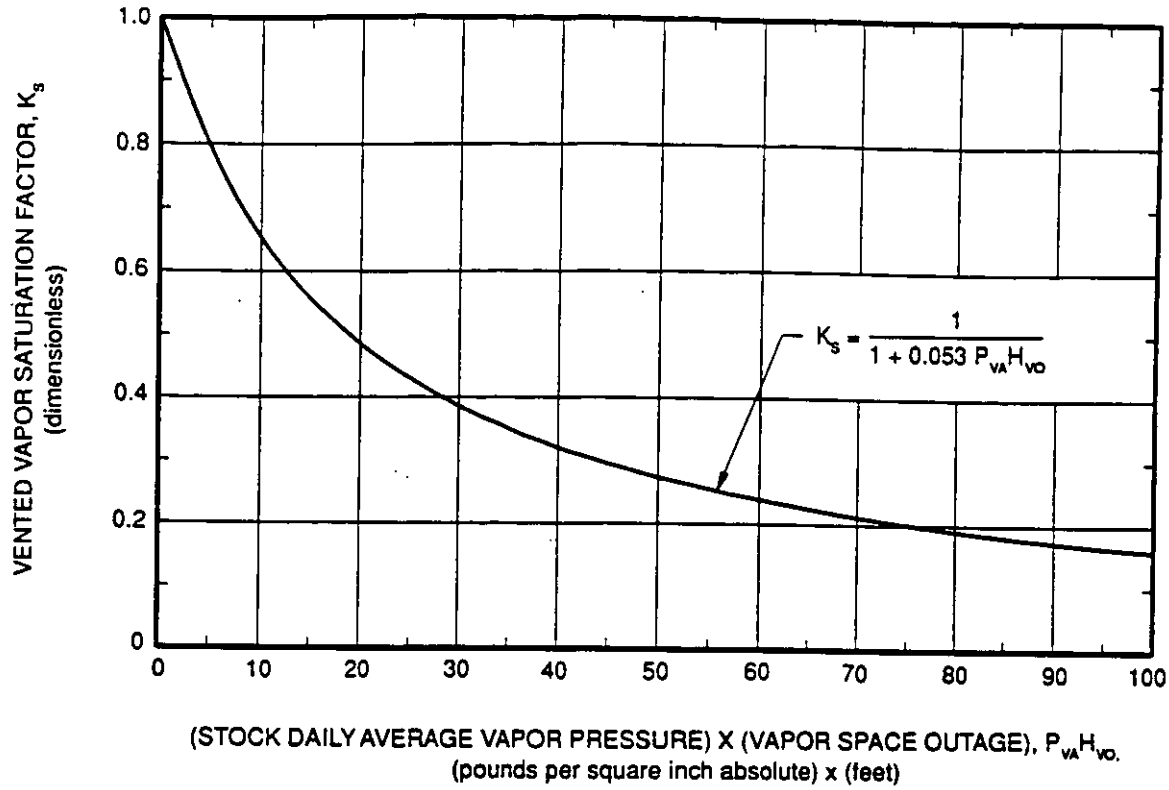


Figure 33 - Vented Vapor Saturation Factor, K_S (dimensionless)

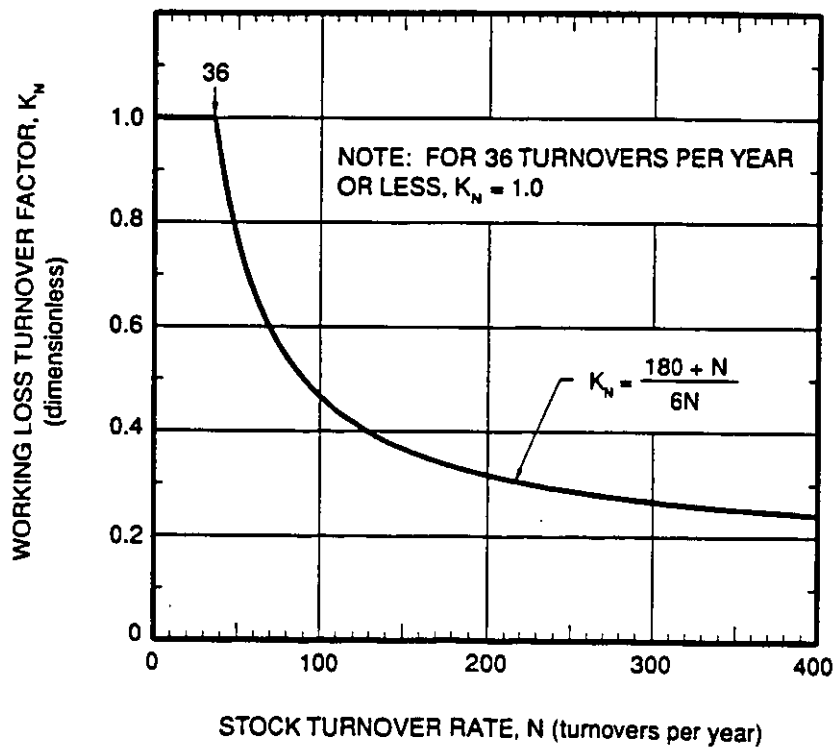


Figure 34 - Working Loss Turnover Factor, K_N (dimensionless)

Table 1 - EFRT Rim Seal Loss Factor, F_R (lb-mole/ft yr), For Average-Fitting Seals

TANK TYPE AND SEAL TYPE	WIND SPEED, V (mi/hr)		
	5	10	15
WELDED TANK			
1. Mechanical-Shoe Seal			
a. Primary Only	13.4	37.9	69.7
b. Shoe-Mounted Secondary	5.52	12.7	20.6
c. Rim-Mounted Secondary	1.00	2.00	3.00
2. Liquid-Mounted Resilient-Filled Seal			
a. Primary Only	5.50	11.0	16.5
b. Weather Shield	3.41	6.35	9.15
c. Rim-Mounted Secondary	1.33	1.76	2.07
3. Vapor-Mounted Resilient-Filled Seal			
a. Primary Only	48.6	239.	608.
b. Weather Shield	31.0	143.	348.
c. Rim-Mounted Secondary	13.1	79.6	228.
RIVETED TANKS			
4. Mechanical-Shoe Seal			
a. Primary Only	14.5	41.1	75.5
b. Shoe-Mounted Secondary	9.66	22.2	36.1
c. Rim-Mounted Secondary	2.63	7.96	15.2

Table 2 - IFRT Rim Seal Loss Factor, F_R (lb-mole/ft yr), For Average-Fitting Seals

TANK TYPE AND SEAL TYPE	F_R (lb-mole/ft yr)
WELDED TANK	
1. Mechanical-Shoe Seal	
a. Primary Only	3.0
b. Rim-Mounted Secondary	1.6
2. Liquid-Mounted Resilient-Filled Seal	
a. Primary Only	3.0
b. Rim-Mounted Secondary	1.6
3. Vapor-Mounted Resilient-Filled Seal	
a. Primary Only	6.7
b. Rim-Mounted Secondary	2.5
4. Flexible-Wiper Seal	
a. Primary Only	6.7
b. Rim-Mounted Secondary	2.5

Table 3 - EFRT Roof Fitting Loss Factor, F_F (lb-mole/yr), For Typical Construction Details

ROOF FITTING TYPE AND CONTRUCTION DETAILS	WIND SPEED, V (mi/hr)		
	5	10	15
1. ACCESS HATCH			
Bolted Cover, Gasketed	0	0	0
2. RIM VENT			
Weighted Actuation, Gasketed	1.21	1.71	2.21
3. GAUGE-HATCH/SAMPLE WELL			
Weighted Actuation, Gasketed	1.65	2.35	3.05
4. VACUUM BREAKER			
Weighted Actuation, Gasketed	2.05	2.90	3.75
5. ROOF LEG			
Adjustable, Pontoon Area	2.50	3.50	4.50
6. GAUGE-FLOAT WELL			
Unbolted Cover, Ungasketed	31.8	61.3	90.8
7. OVERFLOW ROOF DRAIN			
Open	66.6	176	310
8. UNSLOTTED GUIDE-POLE WELL			
Sliding Cover, Ungasketed	324	640	952
9. SLOTTED GUIDE-POLE/SAMPLE WELL			
Sliding Cover, Ungasketed	2,140	4,910	7,990

Table 4 - IFRT Roof Fitting Loss Factor, F_F (lb-mole/yr), For Typical Construction Details

ROOF FITTING TYPE AND CONTRUCTION DETAILS	F_F (lb-mole/yr)
1. VACUUM BREAKER	
Weighted Actuation, Gasketed	0.7
2. STUB DRAIN	1.2
3. ACCESS HATCH	
Bolted Cover, Gasketed	1.6
4. ROOF LEG	
Adjustable	7.9
5. GAUGE-FLOAT WELL	
Unbolted Cover, Ungasketed	28.0
6. COLUMN WELL	
Pipe Column, Sliding Cover, Ungasketed	32.0
7. UNSLOTTED GUIDE-POLE WELL	
Sliding Cover, Ungasketed	32.0
8. SLOTTED GUIDE-POLE/SAMPLE WELL	
Sliding Cover, Ungasketed	57.0
9. LADDER WELL	
Sliding Cover, Ungasketed	76.0

Table 5 - Clingage Factor, C (bbl/1000 ft^2)

PRODUCT STORED	SHELL CONDITION		
	Light Rust	Dense Rust	Gunite Lined
Gasoline	0.0015	0.0075	0.15
Single-Component Stocks	0.0015	0.0075	0.15
Crude Oil	0.0060	0.030	0.60

Table 6 - Solar Absorptance, α (dimensionless)

PAINT COLOR	PAINT SHADE OR TYPE	PAINT CONDITION	
		Good	Poor
Aluminum	Specular	0.39	0.49
Aluminum	Diffuse	0.60	0.68
Gray	Light	0.54	0.63
Gray	Medium	0.68	0.74
Red	Primer	0.89	0.91
White	-----	0.17	0.34

Table 7 - Assumed Conditions for Floating-Roof Tank Sample Problem

CONDITION TYPE	ASSUMED VALUE
PRODUCT CONDITIONS	
Type	Crude Oil
True Vapor Pressure	1.5 psia
Vapor Molecular Weight	50 lb/lb-mole
Liquid Density	7.1 lb/gal
AVERAGE AMBIENT CONDITIONS	
Wind Speed	10 mi/hr
Temperature	60°F
Barometric Pressure	14.7 psia
TANK CONDITIONS	
Tank Types	EFRT, IFRT
Tank Construction	Welded
Diameters	50, 100, 150, 200 ft.
Shell Working Height	50 ft.
EFRT	
Seal Fit	Average Fit
Shell Inner Surface Condition	Light Rust
Floating Roof Construction and Type	Welded Double-Deck
Floating Roof Fitting Types	Typical
IFRT	
Fixed Roof Type	Column Supported
Seal Fit	Average Fit
Columns and Inner Shell Surface Condition	Light Rust
Floating Roof Construction	Welded, Bolted
Floating Roof Fitting Types	Typical
OPERATING CONDITIONS	
Throughput	10 turnovers/yr

Table 8 - Evaporative Loss (lb/yr) for Each Floating-Roof Tank Loss Source Component

LOSS SOURCE COMPONENT	TANK DIAMETER, (ft)			
	50	100	150	200
EXTERNAL FLOATING-ROOF TANK (EFRT)				
A. Rim Seal Loss				
1. Mechanical-Shoe Seal				
a. Primary Only	1,021	2,042	3,062	4,083
b. Rim-Mounted Secondary	54	108	161	215
2. Liquid-Mounted Resilient-Filled Seal				
a. Primary Only	296	592	888	1,184
b. Rim-Mounted Secondary		95	142	189
3. Vapor-Mounted Resilient-Filled Seal				
a. Primary Only	6,4[illegible]	12,882	19,323	25,764
b. Rim-Mounted Secondary	2,142	4,284	6,426	8,567
B. Roof Fitting Loss	383	519	655	791
C. Roof Seam Loss	0	0	0	0
D. Withdrawal Loss	141	281	422	562
INTERNAL FLOATING-ROOF TANK (IFRT)				
A. Rim Seal Loss				
1. Liquid-Mounted Resilient-Filled Seal or Mechanical-Shoe Seal				
a. Primary Only	81	161	242	323
b. Rim-Mounted Secondary	[illegible]	86	129	172
2. Vapor-Mounted Resilient-Filled Seal or Flexible-Wiper Seal				
a. Primary Only	180	360	541	721
b. Rim-Mounted Secondary	67	135	202	269
B. Roof Fitting Loss				
1. Welded Floating Roof	161	354	651	1,051
2. Bolted Floating Roof	174	406	767	1,257
C. Roof Seam Loss				
1. Welded Floating Roof	0	0	0	0
2. Bolted Floating Roof	91	366	823	1,463
D. Withdrawal Loss	143	298	447	624

Table 9 - Total Evaporative Loss (lb/yr) for Floating-Roof Tank Sample Problem

TANK DESCRIPTION	TANK DIAMETER, (ft)			
	50	100	150	200
EXTERNAL FLOATING-ROOF TANK (EFRT)				
A. Welded Floating Roof				
1. Mechanical-Shoe Seal				
a. Primary Only	1,545	2,842	4,139	5,436
b. Rim-Mounted Secondary	578	908	1,238	1,568
2. Liquid-Mounted Resilient-Filled Seal				
a. Primary Only	820	1,392	1,964	2,537
b. Rim-Mounted Secondary	571	895	1,218	1,542
3. Vapor-Mounted Resilient-Filled Seal				
a. Primary Only	6,965	13,682	20,399	27,117
b. Rim-Mounted Secondary	2,666	5,084	7,502	9,921
INTERNAL FLOATING-ROOF TANK (IFRT)				
A. Welded Floating Roof				
1. Liquid-Mounted Resilient-Filled Seal or Mechanical-Shoe Seal				
a. Primary Only	385	814	1,340	1,997
b. Rim-Mounted Secondary	348	738	1,227	1,847
2. Vapor-Mounted Resilient-Filled Seal or Flexible-Wiper Seal				
a. Primary Only	485	1,013	1,638	2,395
b. Rim-Mounted Secondary	372	787	1,299	1,943
B. Bolted Floating Roof				
1. Liquid-Mounted Resilient-Filled Seal or Mechanical-Shoe Seal				
a. Primary Only	490	1,231	2,279	3,667
b. Rim-Mounted Secondary	452	1,156	2,166	3,517
2. Vapor-Mounted Resilient-Filled Seal or Flexible-Wiper Seal				
a. Primary Only	589	1,430	2,578	4,065
b. Rim-Mounted Secondary	476	1,204	2,239	3,613