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Control of Volatile Organic Emissions from Petroleum Liquid Storage in External Floating Roof Tanks

Emission Standards and Engineering Division

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Air, Noise, and Radiation
Office of Air Quality Planning and Standards
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ABBREVIATIONS AND CONVERSION FACTORS

EPA policy is to express all measurements in Agency documents in metric units. Dual units are sometimes given in the text for clarity. Listed below are abbreviations and conversion factors for English equivalents of metric units. Frequently used measurements are also presented in dual units below for the reader's convenience.

METRIC UNIT	ALTERNATE UNIT	CONVERSION
kilogram (kg)	pound (lb) ton	kg x 2.205 = lbs kg x 1.1 x 10^{-3} = tons
metric ton (m ton) or megagram (Mg)	pound (lb) ton	Mg x 2205 = lbs Mg x 1.102 = tons
kilometer (km) kilometers per hour (kph) meter (m) centimeter (cm)	mile (mi) miles per hour (mph) foot (ft) inch (in)	km x 0.621 = mi kph x 0.621 = mph m x 3.281 = ft cm x 0.394 = in
liter (l)	gallon (gal) barrel (bbl)	l x 0.264 = gal l x 6.3 x 10^{-3} = bbl
Pascal (Pa)	atmospheres (atm) pounds per square inch (psi)	Pa x 9.9 x 10^{-6} = atm Pa x 6.7 x 10^{-7} = psi
kiloPascals (kPa)	atmospheres (atm) pounds per square inch (psi)	kPa x 9.9 x 10^{-3} = atm kPa x 0.145 = psi

FREQUENTLY USED MEASUREMENTS

1,600,000 l ∿ 422,000 gal ∿ 10,000 bbl
150,000 l ∿ 40,000 gal ∿ 950 bbl

10.5 kPa ∿ 1.52 psi
13.8 kPa ∿ 2.0 psi
27.6 kPa ∿ 4 psi
41.4 kPa ∿ 6 psi
69.0 kPa ∿ 10 psi

9.7 kph ∿ 6 mph
16.1 kph ∿ 10 mph
22.5 kph ∿ 14 mph

Definition of Terms

A. Condensate means hydrocarbon liquid separated from natural gas which condenses due to changes in the temperature and/or pressure and remains liquid at standard conditions.

B. Cost Effectiveness - Cost (or credit) per megagram of controlled emissions. Given in general by: (recovered petroleum liquid value - net annual control system cost) ÷ (megagrams of controlled emissions) = cost (or credit) /Mg controlled emissions.

C. Crude oil means a naturally occurring mixture consisting of hydrocarbons and/or sulfur, nitrogen and/or oxygen derivatives of hydrocarbons and which is a liquid in the reservoir and at standard conditions.

D. Custody transfer means the transfer of produced crude oil and/or condensate, after processing and/or treating in the producing operations, from storage tanks or automatic transfer facilities to pipelines or any other forms of transportation.

E. External floating roof means a storage vessel cover in an open top tank consisting of a double deck or pontoon single deck which rests upon and is supported by the petroleum liquid being contained and is equipped with a closure seal or seals to close the space between the roof edge and tank shell.

F. Internal floating roof means a cover or roof in a fixed roof tank which rests upon or is floated upon the petroleum liquid being contained, and is equipped with a closure seal or seals to close the space between the roof edge and tank shell.

G. Liquid-mounted means a primary seal mounted so the bottom of the seal covers the liquid surface between the tank shell and the floating roof.

H. Vapor-mounted means a primary seal mounted so there is an annular vapor space underneath the seal. The annular vapor space is bounded by the bottom of the primary seal, the tank shell, the liquid surface, and the floating roof.

I. Petroleum liquids means crude oil, condensate, and any finished or intermediate products manufactured or extracted in a petroleum refinery.

J. True vapor pressure means the equilibrium partial pressure exerted by a petroleum liquid as determined in accordance with methods described in American Petroleum Institute (API) Bulletin 2517, Evaporation Loss from Floating Roof Tanks, 1962. The API procedure may not be applicable to some high viscosity or high pour crudes. Available estimates of true vapor pressure may be used in special cases such as these.

K. Volatile Organic Compounds (VOC) means compounds which under favorable conditions may participate in photochemical reactions to form oxidants.

1.0 INTRODUCTION

This document is related to the control of volatile organic compounds (VOC) from the storage of petroleum liquids in external floating roof tanks.

Methodology described in this document represents the presumptive norm or reasonably available control technology (RACT) that can be applied to existing external floating roof storage tanks. RACT is defined as the lowest emission limit that a particular source is capable of meeting by the application of control technology that is reasonably available considering technological and economic feasibility. It may require technology that has been applied to similar, but not necessarily identical, source categories. It is not intended that extensive research and development be conducted before a given control technology can be applied to the source. This does not, however, preclude requiring a short-term evaluation program to permit the application of a given technology to a particular source. The latter effort is an appropriate technology-forcing aspect of RACT.

1.1 NEED TO REGULATE

Control techniques guidelines concerning RACT are being prepared for those industries that emit significant quantities of air pollutants in areas of the country where National Ambient Air Quality Standards (NAAQS) are not being attained. Storage tanks for petroleum liquids are a significant source of VOC. A control techniques guideline (CTG) for storage of petroleum liquids in fixed roof tanks (EPA-450/2-77-036) was published in December 1977. RACT for fixed roof tanks was defined as the retrofit with internal floating roofs or equivalent.

The following recommended control measures apply to external floating roof tanks (EFRT) larger than 150,000 liters (950 bbls) storing petroleum liquids. They do not apply to fixed roof or tanks with or without internal floating roofs, nor do they apply to small production tanks. In general, RACT for external floating roof tanks (EFRT) is defined as follows:

(1) A welded EFRT equipped with primary metallic shoe or liquid-mounted seals is required to retrofit with a rim-mounted secondary seal if the TVP of the stored liquid exceeds 27.6 kPa (4 psi).

(2) A welded or riveted EFRT equipped with primary vapor-mounted seals is required to retrofit with a rim-mounted secondary if the TVP of the stored liquid exceeds 10.5 kPa (1.5 psi).

(3) A riveted EFRT equipped with primary metallic shoe or liquid-mounted seals is also required to retrofit with a rim-mounted secondary if the TVP of the stored liquid exceeds 10.5 kPa (1.5 psi).

Specific recommendations for regulations, including exemptions, are presented in Chapter 5.0.

Estimated emissions from the affected EFRT's during 1978 were 65,000 megagrams/year (71,630 tons/yr). The proposed recommendations would reduce these emissions to 30,000 megagrams/year (33,060 tons/yr).

The emission estimates used in this document were calculated from data obtained by Chicago Bridge and Iron Company (CBI) on a 6.1 m (20 ft) diameter test tank. Data obtained by Pittsburgh-Des Moines Steel Company (PDM) on a 10.7 m (35 ft) diameter test tank were used to verify RACT for liquid-mounted seals which are liquid or foam filled. An American Petroleum Institute (API) emission test program, scheduled for completion in 1979, is expected to provide verification of the validity of the scale-up techniques used herein.

Cost effectiveness of retrofitting rim-mounted secondary seals to EFRT's is dependent on tank size, product type, product value, average wind speed and other factors. For example, the installed capital cost for retrofitting a rim-mounted secondary seal to a 30.5 m (100 ft) diameter welded tank equipped with a primary shoe seal is about $17,000. The net annual cost after credit for recovered product is $3,140 when storing gasoline at a TVP of 41.4 kPa (6 psi) and an average wind speed of 16.1 kph (10 mph). A welded tank having a vapor-mounted primary seal and a riveted tank having a primary metallic shoe seal can be retrofitted with a rim-mounted secondary seal for the same capital cost. However, in these two cases under the same storage conditions the emission reductions are larger and the net annual cost is $1930 for the welded tank with the vapor-mounted seal and $1750 for the riveted tank with the shoe seal. The cost effectiveness for the above three cases is $373, $117, and $99 per megagram of emissions controlled, respectively. At lower wind speeds and vapor pressures, the cost effectiveness would be higher. At higher wind speeds and vapor pressures, the cost effectiveness would be lower.

2.0 SOURCES AND TYPES OF EMISSIONS

There are an estimated 13,800 internal and external floating roof tanks storing petroleum liquids at refineries, terminals, tank farms and along pipelines.[1] Of these, 10,700 are storing liquids whose vapor pressures equal or exceed 10.5 kPa. Data are not available to establish how many of these are external floating roof tanks.

2.1 EXTERNAL FLOATING ROOF TANKS

An external floating roof tank consists of a steel cylindrical shell equipped with a deck or roof which floats on the surface of the stored liquid, rising and falling with the liquid level (Figure 2-1). The liquid surface is completely covered by the floating roof except in the small annular space between the roof and the shell. A seal attached to the roof contacts the tank wall and covers the remaining area. The seal slides against the tank wall as the roof is raised or lowered. The primary route of VOC emissions is by this seal.

When a commercial fit between the seal and the tank wall is maintained, most losses by the seal are attributable to the wind.[2,3,4,5,6] Wind induced losses occur when air flow across the tank creates pressure differences around the floating roof, causing air to flow into the annular vapor space* on the leeward side and air plus VOC to flow out on the windward side. Improper or loose fit

* Unless the primary seal is liquid-mounted, the vapor space bounded by the sliding seal, wall, roof, and liquid surface defines an annular vapor space.

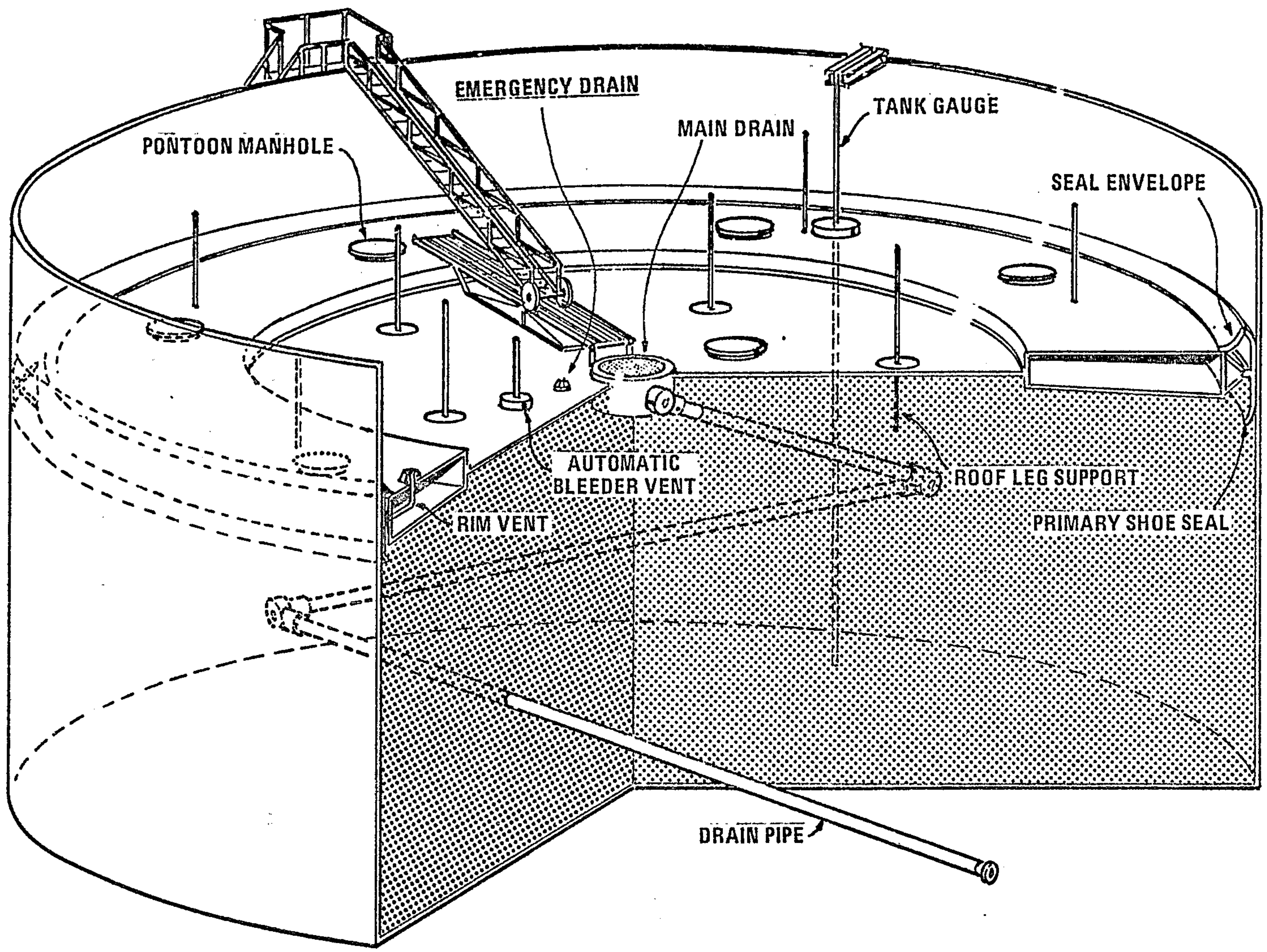


Figure 2-1. External floating roof tank (pontoon type).

of the seal creates gaps or openings between the seal and the tank wall. These gaps expose the liquid surface directly to the wind and sun, which combine to increase emissions. The wind flows across the tank, scouring the vapor space and sweeping away VOC. In addition, leakage through holes in the envelope (the fabric cover that is used to bridge the space between the seal and the floating roof) or around the envelope attachment bolts can be a significant source of loss from shoe seals.

Other causes of emissions are: (1) release of dissolved air saturated with VOC because of barometric pressure changes; (2) solar heating of liquid in the rim space which increases liquid vapor pressure and VOC migration; (3) evaporation of the liquid which clings to the tank wall when the tank is being emptied (wetting losses)[7]; (4) breathing of the vapor space due to changes in the ambient temperature or barometric pressure; or (5) changes in the bulk liquid temperature. Wind-induced losses are larger than all of these.

2.2 PRIMARY SEALS

There are basically three types of primary seals; mechanical shoe seals, resilient foam seals, and liquid-filled seals. Although there are other designs, these three comprise the vast majority of primary seals in use today.

A weather guard is often installed over primary seals to protect the seals from deterioration caused by dust, rain or sunlight. Typically, a weather guard is an arrangement of overlapping thin metal sheets pivoted from the floating roof to ride against the tank wall. This helps protect the product from contamination, but its effect on gaps and hence wind-induced emissions is variable. Some weather guard designs could do little to curb emissions where other tighter designs may be reasonably effective over certain types of primary or secondary seals. Because of the uncertainties associated with emissions control, the weather guard is not usually considered as effective an emission control device as a secondary seal.

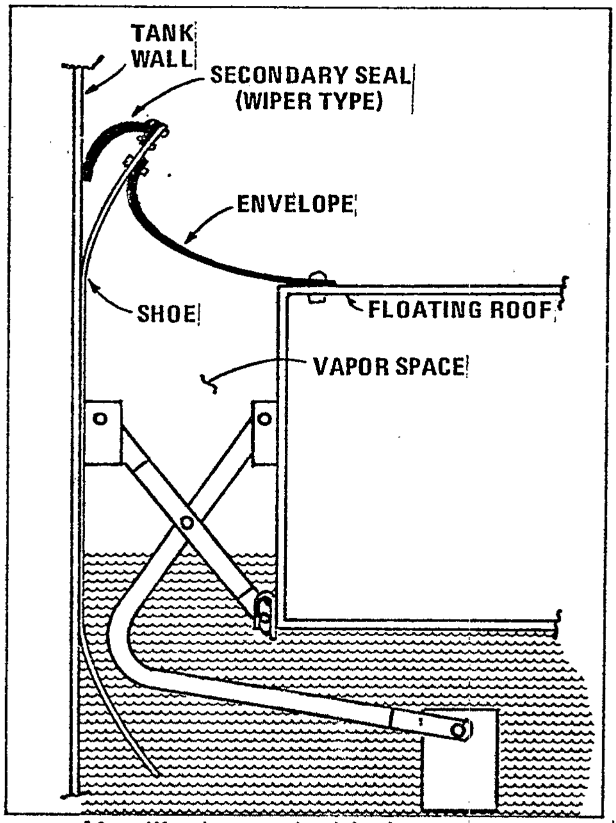
2.2.1 Mechanical Shoe Seal

The mechanical shoe seal is characterized by a 75 to 130 cm (30" to 51") high metal sheet (the "shoe") held against the vertical tank wall (Figure 2-2a). The shoe is connected by braces to the floating roof and is held tight against the wall by springs or weighted levers. A flexible coated fabric (the "envelope") is suspended from the shoe seal to the floating roof to close the annular space between the roof and the primary seal.

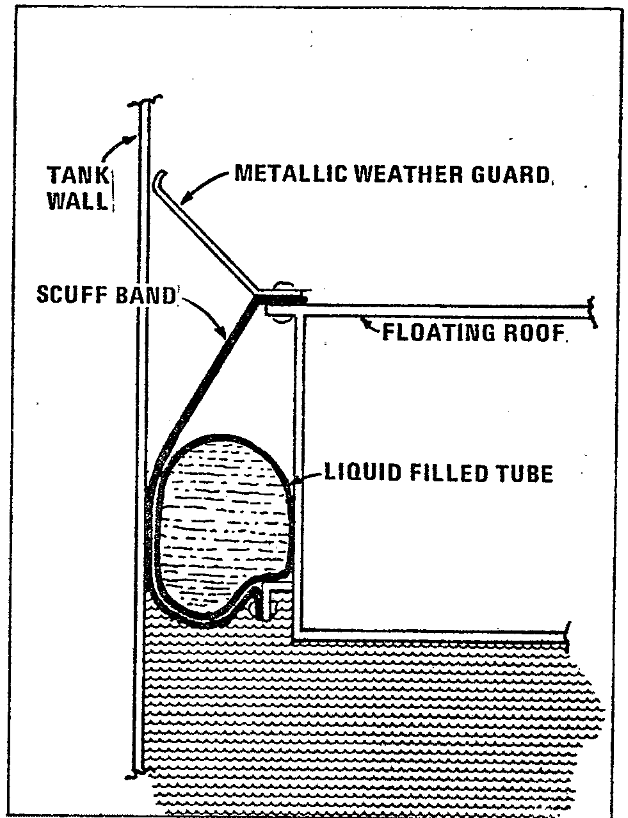
Emissions from the mechanical shoe seal occur from the exposed liquid surface in the gap spaces between the shoe and the tank wall, and through openings in the envelope or shoe. Close fitting primary shoe seals effectively reduce emissions from the liquid surface in the gap space, as do shoe-mounted secondary seals (Figure 2-2a).[8] Shoe-mounted secondary seals are discussed in Chapter 3.0. Emissions are also affected by the envelope and shoe conditions. Holes, tears, or other openings in the envelope or shoe allow direct communication between the annular vapor space and the atmosphere. Through these openings, the wind can scour the vapor space, exiting with VOC laden vapors.

2.2.2 Resilient Foam Seal

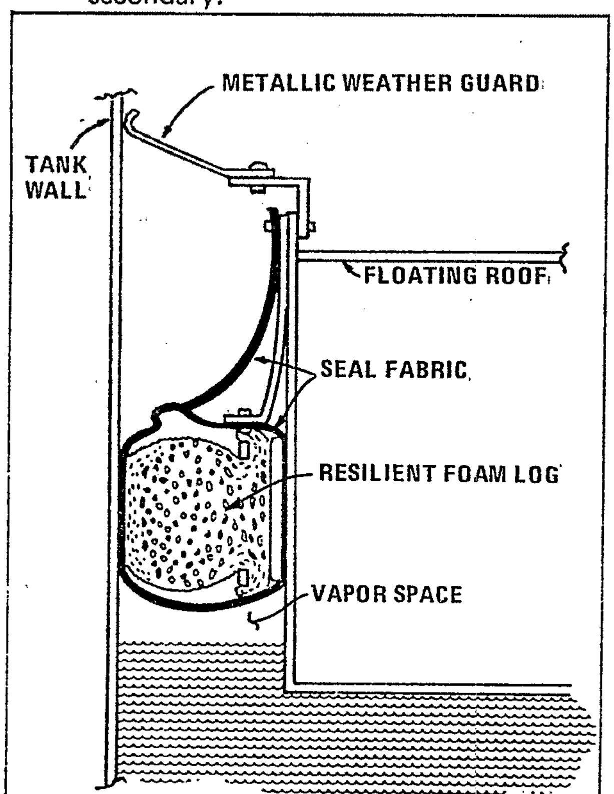
As illustrated in Figure 2-2c,d, resilient foam primary seals fill the annular space between the floating roof and tank wall with a continuous compressible foam log encased in a protective tube. The resiliency of the foam log allows the seal to adapt itself to some imperfections in tank dimensions and even to fill or partially fill some protrusions. The foam log may be vapor-mounted (Figure 2-2c) or liquid-mounted (Figure 2-2d).



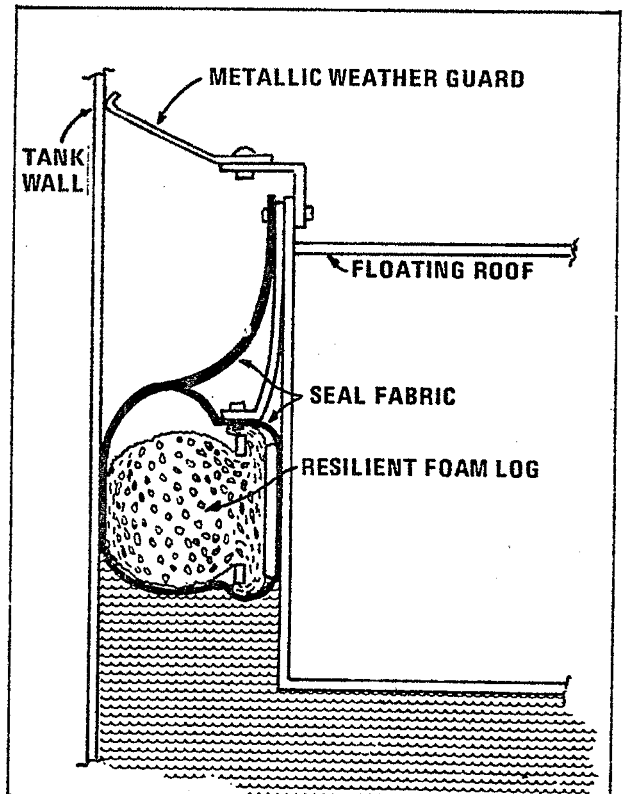
a. Metallic shoe seal with shoe-mounted secondary.



b. Liquid-filled seal with weather guard.



c. Resilient foam seal with weather guard (vapor-mounted).



d. Resilient foam seal with weather guard (liquid-mounted).

Figure 2-2 Primary Seals

When a foam seal is vapor-mounted emissions can be much higher than when liquid-mounted. A gap between a vapor-mounted foam seal and the wall allows direct communication between the atmosphere and the vapor space bounded by the seal, the roof, the tank wall, and the product liquid.

When a foam seal is liquid-mounted, the vapor space is eliminated and losses are comparable in magnitude to those for the shoe seal.

2.2.3 Liquid-Filled Seal

A liquid-filled seal may be a tough fabric band or envelope filled with a liquid, or it may be a 20-25 cm (8-10") diameter flexible polymeric tube filled with a liquid and sheathed with a tough fabric scuff band (Figure 2-2b). The liquid is commonly a petroleum distillate or other liquid that would not contaminate the stored product if the tube ruptured. Liquid-filled seals are mounted on the product liquid surface with no vapor space. They are usually protected by a weatherguard.

Losses from tanks equipped with liquid-mounted liquid-filled primary seals are comparable in magnitude to shoe seals and liquid-mounted foam seals.[9]

2.3 REFERENCES

1. Evaluation of Hydrocarbon Emissions from Petroleum Liquid Storage, EPA-450/3-78-012, March, 1978.

2. SOHIO/CBI Floating Roof Emission Program, Interim Report, October 7, 1976.

3. SOHIO/CBI Floating Roof Tank Emission Program, Final Report, November, 1976.

4. Western Oil and Gas Association, Metallic Sealing Ring Emission Test Program, Interim Report, Chicago Bridge & Iron Company, January, 1977.

5. Western Oil and Gas Association, Metallic Sealing Ring Emission Test Program, Final Report, Chicago Bridge & Iron Company, March, 1977.

6. Western Oil and Gas Association, Metallic Sealing Ring Emission Test Program, Supplemental Report, Chicago Bridge & Iron Company, June, 1977.

7. SOHIO/CBI Floating Roof Tank Emission Test Program, Supplemental Report, Chicago Bridge & Iron Company, February 15, 1977.

8. Floating Roof Seal Development - Emission Test Measurement on Proposed CBI Wiper-Type Secondary Seal for SR-1 Seals, Chicago Bridge & Iron Company, February 23, 1977.

9. Measurement of Emissions from a Tube Seal[R] Equipped Floating Roof Tank, Pittsburgh-Des Moines Steel Company, October 9, 1978.

3.0 CONTROL TECHNOLOGY

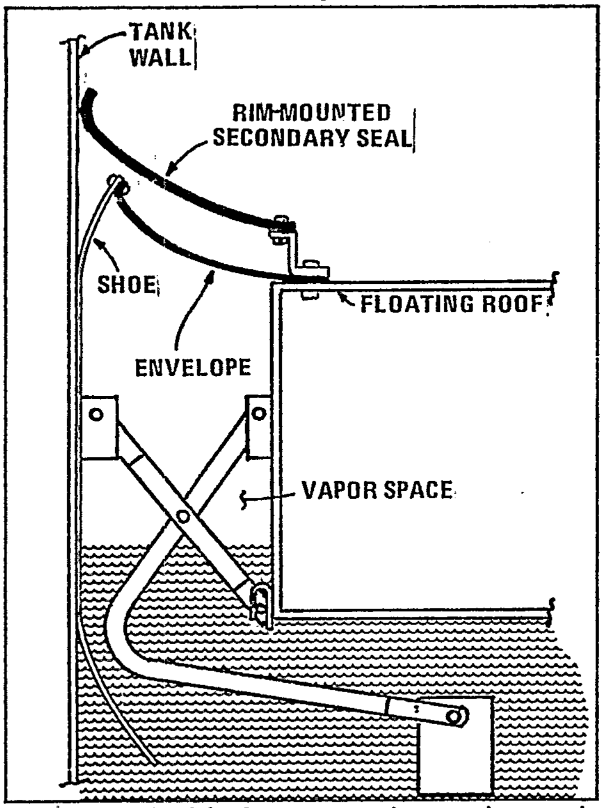
Recommended control technology for existing external floating roof tanks with primary foam, liquid-filled, and metallic shoe seals is retrofitting with a rim-mounted secondary seal. A rim-mounted secondary seal is defined as a continuous device extending from the floating roof to the tank wall, and installed over the primary seal.

3.1 RIM-MOUNTED SECONDARY SEAL

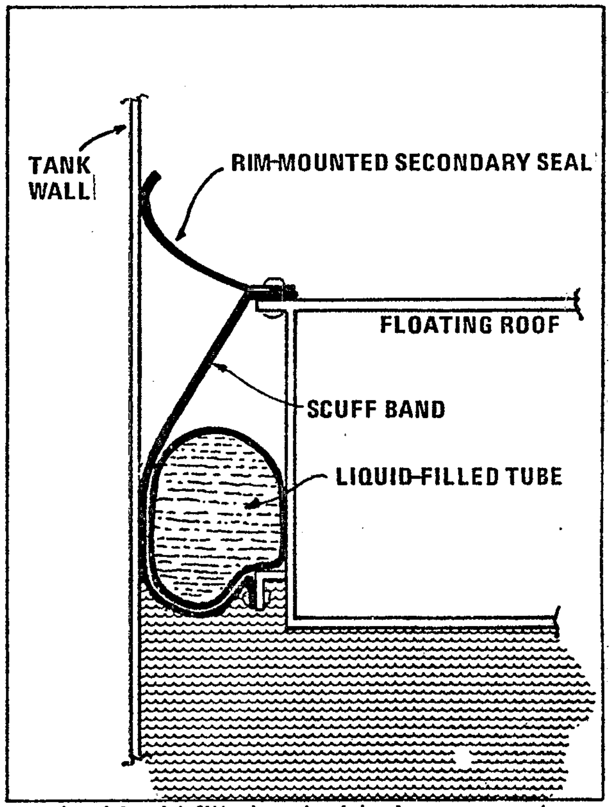
A rim-mounted secondary seal is continuous and extends from the floating roof to the tank wall, covering the entire primary seal. Installed over a mechanical shoe seal, this secondary seal can effectively control VOC that escape from the small vapor space between the shoe and the wall, and through any openings or tears in the seal envelope which would permit direct communication of the seal system vapor space with the atmosphere (see Figure 3.1.a).

Rim-mounted secondary seals are effective in controlling emissions from the liquid and vapor-mounted primary seals shown in Figure 3.1.[1,2,3,4,5] The secondary seals can often be rendered inoperative by cooling and hardening of waxy, heavy pour crude oils. These crudes cause a deposit on the tank wall which is scraped onto the roof when the tank is worked, damaging the secondary seal.

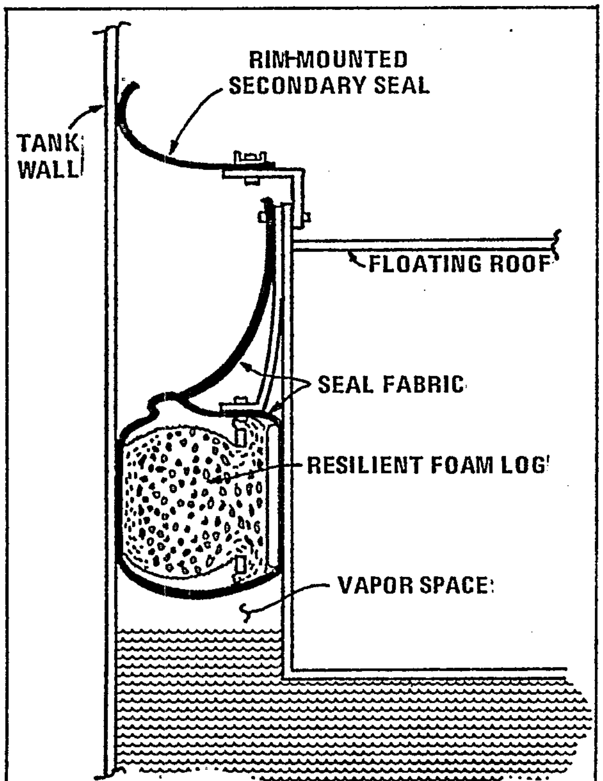
Another type of secondary seal that is commonly installed on external floating roof tanks is a shoe-mounted secondary seal. A shoe-mounted



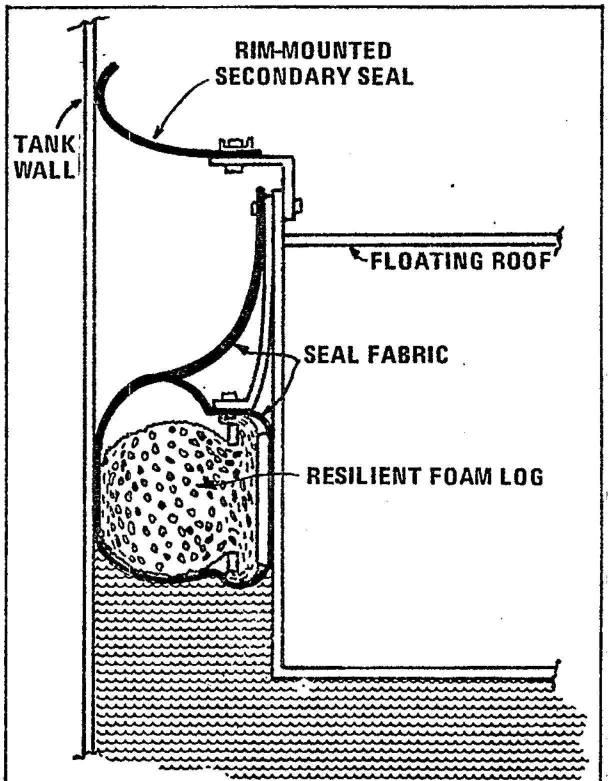
a. Shoe seal with rim-mounted secondary seal.



b. Liquid-filled seal with rim-mounted secondary seal.



c. Resilient foam seal (vapor-mounted). with rim-mounted secondary



d. Resilient foam seal (liquid-mounted). with rim-mounted secondary seal

Figure 3-1 Rim-Mounted Secondary Seals

seal extends from the top of the shoe to the tank wall (see Figure 2-2a).

Shoe-mounted seals do not provide protection against VOC leakage through the envelope. Holes, gaps, tears, or other defects in the envelope can allow direct communication between the saturated vapor under the envelope and the atmosphere and the wind can enter this space through envelope defects, flow around the circumference and exit with saturated or near saturated vapors.

3.2 WIND INDUCED EMISSIONS*

Three 30.5 m (100 ft) diameter tanks were chosen as base cases for emission calculations; a welded tank with a primary shoe seal, a welded tank with a vapor-mounted resilient foam seal, and a riveted tank with a primary shoe seal. The emission reduction that would occur from installing a secondary seal over each of these base cases is discussed below.

3.2.1 Shoe Seals on Welded Tanks

When storing a 27.6 kPa (4 psi) vapor pressure product, a rim-mounted secondary seal installed over a primary shoe seal reduces emissions from 11.2 megagrams per year (Figure 3-2a) to 2.8 megagrams per year (Figure 3-2d). A shoe-mounted seal installed on a primary shoe seal reduces emissions from 11.2 megagrams per year to 5.3 megagrams per year (Figure 3.2c) for the same product. Emission reductions for various seal configurations are best illustrated over a range of product vapor pressures by Figure 3-2.

The amount of emissions curbed for each progressively stricter control option increases as the TVP of the stored liquid increases. For example, by subtracting (d) from (a) in Figure 3-2, the emission reduction for installing

* The emission rates throughout this chapter are calculated for a 30.5 m (100 ft) diameter tank storing 41.4 kPa (6 psi) vapor pressure gasoline with an average wind speed of 16.1 kph (10 mph). The average vapor molecular weight was assumed to be 65, typical for gasoline. Emission rates may be scaled according to Appendix B.

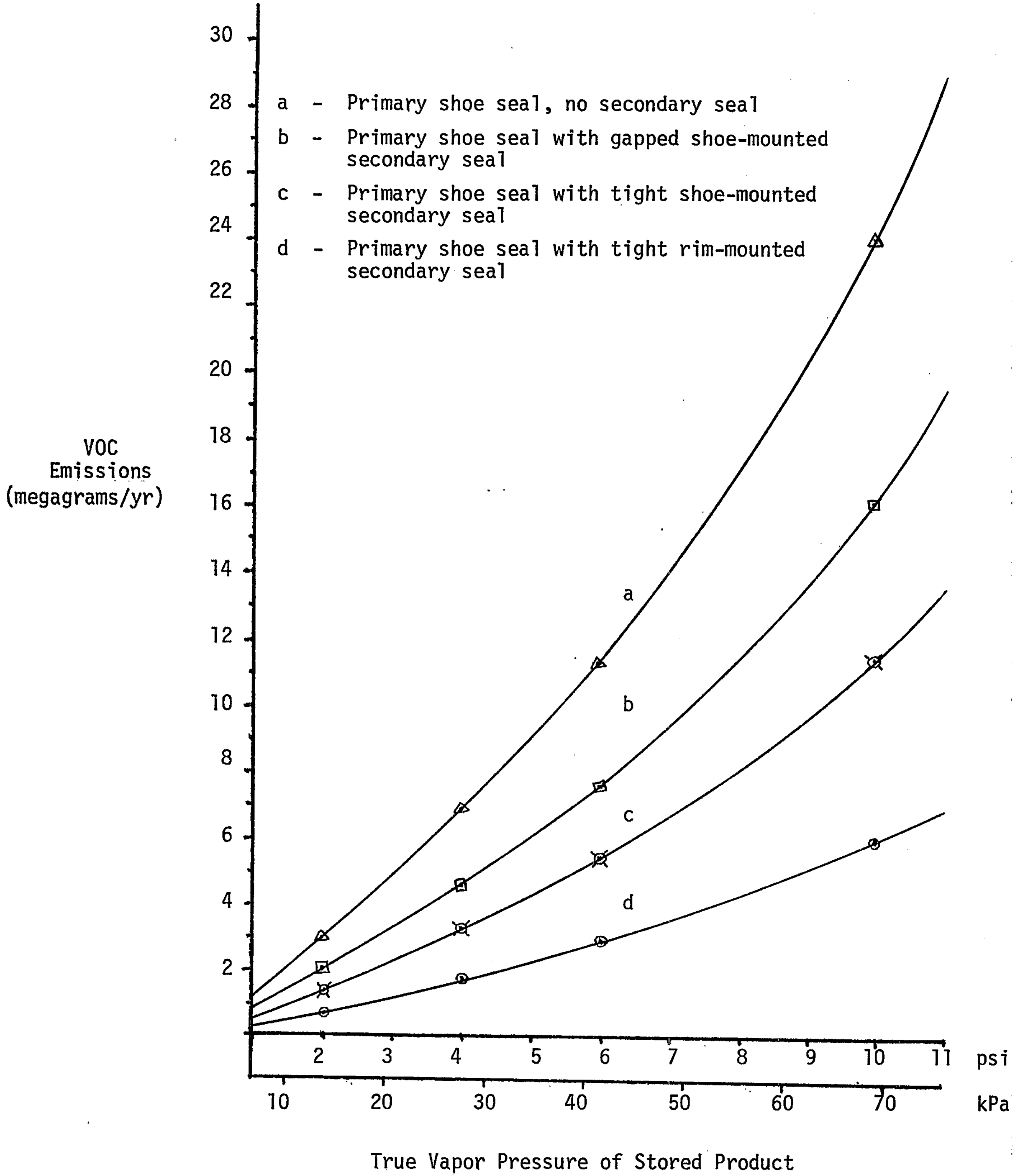


Figure 3-2. EMISSIONS FROM 30.5 m (100 ft) DIAMETER WELDED GASOLINE TANK WITH PRIMARY SHOE SEAL AT 16.1 kph (10 mph) AVERAGE WIND SPEED

a rim-mounted secondary seal over a primary shoe seal is only about 5.1 megagrams per year for storing a 27.6 kPa (4 psi) product, but the reduction increases to 18 megagrams per year if the stored liquid has a TVP of 69 kPa (10 psi).

Emissions from a tank equipped with a shoe seal and shoe-mounted secondary seal storing 41.4 kPa (6 psi) vapor pressure product are 5.3 megagrams per year. Retrofitting this tank with a rim-mounted secondary seal would reduce emissions by only 2.5 megagrams per year. Thus, tanks now equipped with a primary shoe seal and a shoe-mounted seal are controlled reasonably well and need not be retrofitted with a rim-mounted secondary seal. Nevertheless, the susceptibility of this system to envelope leaks and gaps make good inspection and maintenance practices imperative. A shoe seal without any secondary seal should not be retrofitted with a shoe-mounted secondary.

3.2.2 Liquid-Mounted Resilient Foam and Liquid-Filled Seals on Welded Tanks

Liquid-mounted resilient foam and liquid-filled primary seals have approximately the same emission rates as primary shoe seals and exhibit the same emission reduction trends with control (see Figure 3-2,c). However in some cases the stored liquid may be harmful to the seal, making liquid-mounting impractical.

3.2.3 Vapor-Mounted Resilient Foam Seal on Welded Tank

As discussed in Section 2.2.2, this primary seal has the potential for high emissions when vapor-mounted. These emissions can be effectively controlled by retrofitting with a rim-mounted secondary seal provided the gap between the secondary seal and tank wall is carefully controlled. This is illustrated in Figure 3.3

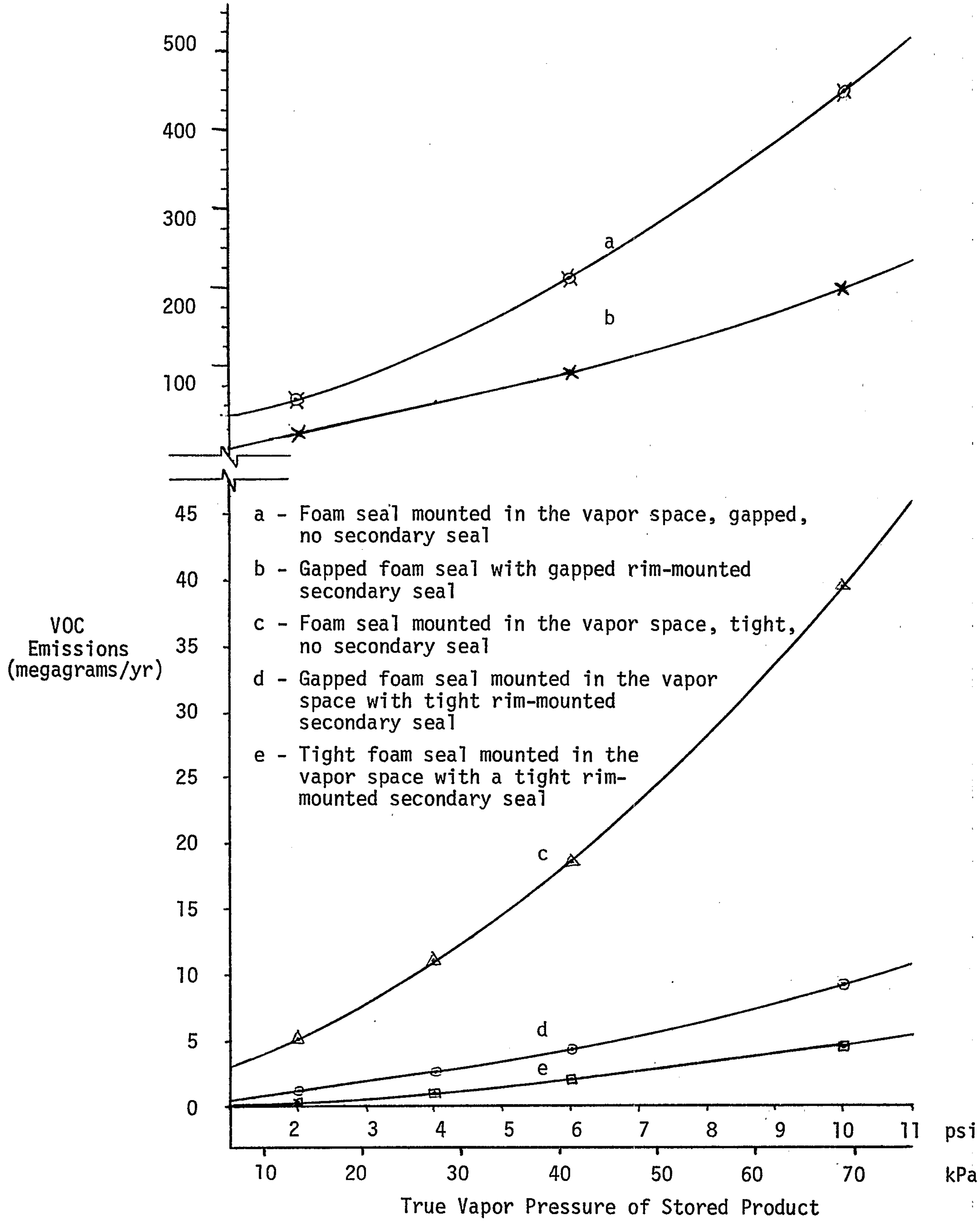


Figure 3.3. EMISSIONS FROM 100 FT DIAMETER WELDED GASOLINE TANK WITH PRIMARY FOAM SEAL, 16.1 kph (10 mph) AVERAGE WIND SPEED

Emissions from a tank storing a 41.4 kPa (6 psi) vapor pressure product equipped with a vapor-mounted resilient foam seal are 18.6 megagrams per year if the primary seal has a tight commercial fit (Figure 3-3c) and 212 megagrams per year if the primary seal is slightly gapped (Figure 3-3a). With a tight rim-mounted secondary seal, emissions from a gapped primary seal are reduced from 212 megagrams per year to 4.3 megagrams per year (Figure 3-3d). When installed over a tight primary seal, emissions are reduced from 18.6 megagrams per year to 2.2 megagrams per year (Figure 3-3e). With a gapped primary seal and a gapped secondary seal, emissions are 95.3 megagrams per year (Figure 3-3b).

3.2.4 Riveted Tanks

Riveted tanks present special problems regardless of primary seal design. The primary seal must ride over the protruding rivet heads when the tank is being worked, creating gaps. If the primary seal stops or is riding on a row of rivet heads, the gaps can be nearly continuous and the wind-induced emissions extremely high. The portion of the seal riding on the rivets (and the riveted members) depends on design, and varies with location in the tank. Emissions based on experimental tests conducted to evaluate a shoe seal in contact with a "worst case" simulated rivet row are shown in Figure 3-4a.[6]

Installation of a rim-mounted secondary seal over this primary shoe seal reduces emissions from 39.9 to 22.3 megagrams per year based on one test and to 7.1 megagrams per year based on another (the only difference being the rivet row design with which the secondary seal was in contact). At more favorable roof locations in a riveted tank, emissions will be lower. Emissions from a welded tank with a rim-mounted secondary were 2.8 megagrams per year.

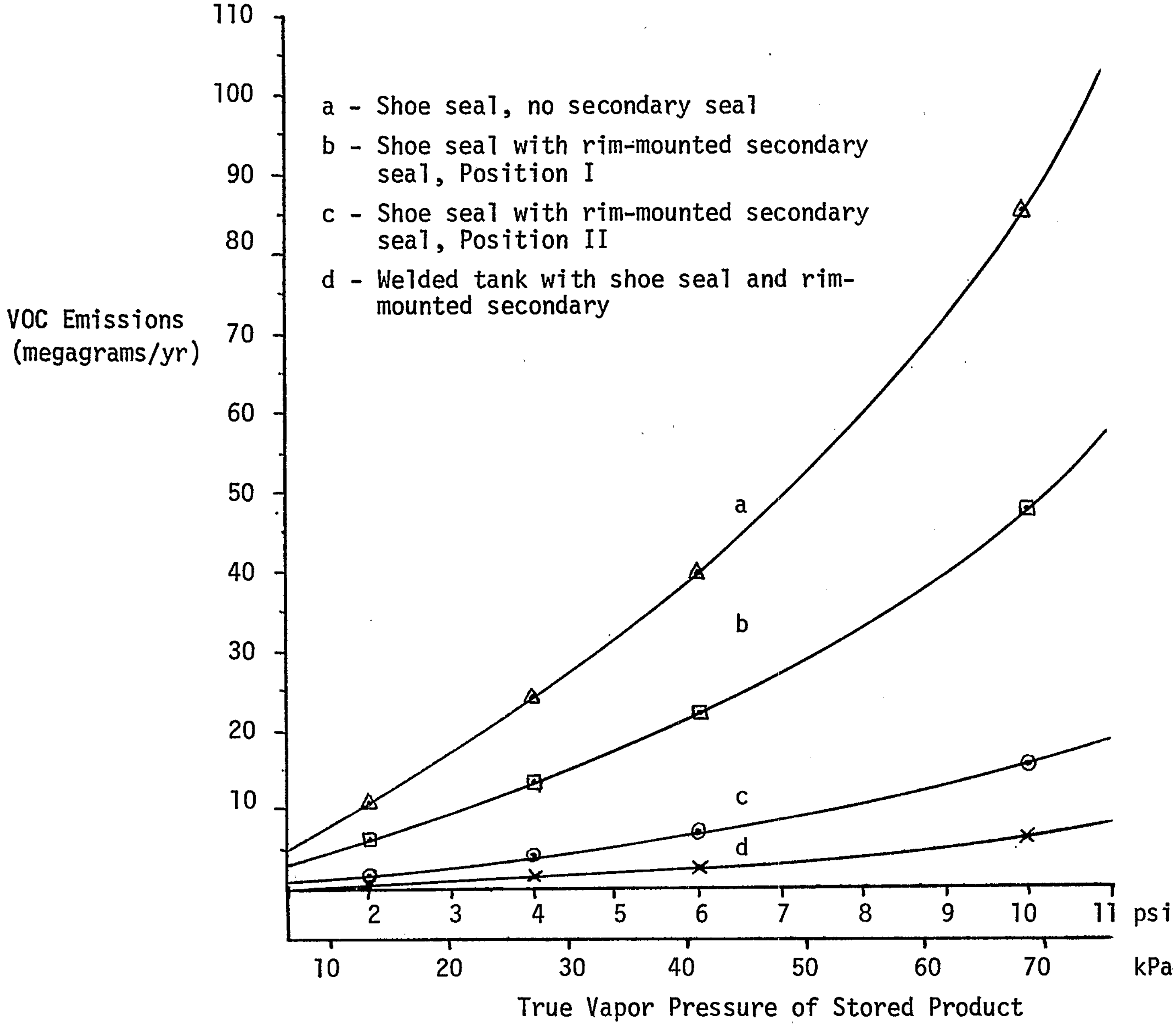


Figure 3-4. EMISSIONS FROM 30.5 m (100 ft) DIAMETER RIVETED GASOLINE TANK WITH PRIMARY SHOE SEAL AT 16.1 kph (10 mph) AVERAGE WIND SPEED

Rivet heads are particularly harsh on primary seals, and seal condition may deteriorate more rapidly. Frequent inspections and good maintenance practices must be followed to control emissions from riveted tanks.

3.3 REFERENCES

1. SOHIO/CBI Floating Roof Emission Program, Interim Report, October 7, 1976.

2. SOHIO/CBI Floating Roof Tank Emission Program, Final Report, November, 1976.

3. Western Oil and Gas Association, Metallic Sealing Ring Emission Test Program, Interim Report, Chicago Bridge & Iron Company, January, 1977.

4. Western Oil and Gas Association, Metallic Sealing Ring Emission Test Program, Final Report, Chicago Bridge & Iron Company, March, 1977.

5. Measurement of Emissions from a Tube Seal[R] Equipped Floating Roof Tank, Pittsburgh-Des Moines Steel Company, October 9, 1978.

6. Western Oil and Gas Association, Metallic Sealing Ring Emission Test Program, Supplemental Report, June, 1977.

4.0 COST ANALYSIS

4.1 INTRODUCTION

4.1.1 Purpose

The purpose of this chapter is to present estimated costs for control of volatile organic compound (VOC) emissions from existing external floating roof petroleum liquid storage tanks.

4.1.2 Scope

Estimates of capital and annualized costs are presented for controlling emissions from existing external floating roof storage tanks. The estimates pertain to welded and riveted steel tanks used for storing gasoline. Current standards for floating roof tanks require the use of single closure (primary) seals, so the cost of control is limited to the additional cost of installing (retrofitting) a secondary seal on existing tanks. Control costs are developed for a model existing external floating roof tank with a diameter of 30.5 m (100 ft), a height of 12.2 m (40 ft) and a storage capacity of 8,910,000 liters. A range of cost effectiveness ratios are presented for storing gasoline that allow for varying operating conditions, locations, and control costs of tanks.

4.1.3 Use of Model Storage Tanks

Gasoline storage tanks vary in size with typical diameters ranging from less than 9.1 m (30 ft) to more than 91.5 m (300 ft). Since it would be impractical to determine costs for all tank sizes, a middle size model was selected for this cost analysis. Table 4-1 presents the cases evaluated

Table 4-1. TECHNICAL PARAMETERS USED IN DEVELOPING GASOLINE STORAGE TANK CONTROL COSTS

I. Storage Tank Size:

Diameter:	30.5 m (100 ft)
Height:	12.2 m (40 ft)
Capacity:	8,910,000 liters
	8,910 m^3 (55,000 bbls)

II. Wind Speed and Vapor Pressure

9.7 kph (6 mph)	13.8 kPa (1.52 psi)
16.1 kph (10 mph)	27.6 kPa (2.0 psi)
22.5 kph (14 mph)	41.4 kPa (6.0 psi)
	69.0 kPa (10.0 psi)

III. VOC Control Efficiencies: (see Table B-2, Appendix B)

Rim mounted secondary seals on floating roof tanks:

a. Case I - Welded tank with the following primary seals - shoe seal, liquid-mounted foam seal, or liquid-mounted liquid-filled seal - (75%)

b. Case II - Welded tank with the following primary seal - a vapor-mounted foam seal - (84 - 88%)

c. Case III - Riveted tank with the following primary seal - a metallic shoe seal - (45%)

Table 4-1 (Continued) TECHNICAL PARAMETERS USED IN DEVELOPING GASOLINE STORAGE TANK CONTROL COSTS

IV. Emissions Before Control (Mg/yr):[a]

CASE	I			II			III		
Wind Velocity	9.7 kph	16.1 kph	22.5 kph	9.7 kph	16.1 kph	22.5 kph	9.7 kph	16.1 kph	22.5 kph
True Vapor Pressure									
13.8 kPa	1.55	3.15	5.60	3.02	5.21	7.33	6.89	11.20	15.51
27.6 kPa	3.36	6.82	12.15	6.54	11.30	15.88	14.95	24.29	33.63
41.4 kPa	5.53	11.22	19.98	10.76	18.60	25.88	24.59	39.95	55.32
69.0 kPa	11.78	23.90	42.54	22.90	39.59	55.60	52.35	85.07	117.70

NOTE: All cases - primary seals - no secondary

V. Emission After Control (Mg/yr):[a]

CASE	I			II			III		
Wind Velocity	9.7 kph	16.1 kph	22.5 kph	9.7 kph	16.1 kph	22.5 kph	9.7 kph	16.1 kph	22.5 kph
True Vapor Pressure									
13.8 kPa	.39	.79	1.40	.35	.61	1.16	3.79	6.25	8.61
27.6 kPa	.83	1.70	3.04	.76	1.31	2.52	8.22	13.54	18.68
41.4 kPa	1.38	2.81	5.00	1.25	2.16	4.15	13.53	22.29	30.75
69.0 kPa	2.94	5.97	10.64	2.66	4.59	8.83	28.80	47.44	65.44

NOTE: All cases - A rim-mounted secondary was used over the specified primary seal.

Table 4-1 (Continued). TECHNICAL PARAMETERS USED IN DEVELOPING GASOLINE STORAGE TANK CONTROL COSTS

VI. Emissions Controlled (Mg/yr):[a]

CASE	I			II			III		
Wind Velocity	9.7 kph	16.1 kph	22.5 kph	9.7 kph	16.1 kph	22.5 kph	9.7 kph	16.1 kph	22.5 kph
True Vapor Pressure									
13.8 kPa	1.16	2.36	4.20	2.67	4.60	6.17	3.10	4.95	6.90
27.6 kPa	2.53	5.12	9.11	5.78	9.99	13.36	6.73	10.75	14.95
41.4 kPa	4.15	8.41	14.98	9.51	16.44	21.73	11.06	17.66	24.57
69.0 kPa	8.84	17.93	31.90	20.24	35.00	46.77	23.55	37.63	52.62

[a]Reference Appendix A and B.

and the technical parameters used in the analysis. The parameters were selected as being representative of average annual wind speed on the United States Gulf Coast, East Coast and West Coast, respectively, and expected ranges of product true vapor pressure at stored temperatures. Emissions and emission reductions are based on extrapolations from a 6.1 m (20 ft) diameter test tank to the full size model tank (see Appendix A and B).[1] It will be noted from Table B-2, Appendix B, that Cases II and III do not represent predictions of maximum achievable emission reductions. Accordingly, cost effectiveness for these cases (see Section 4.3) are conservatively high.

4.1.4 Bases for Capital and Annualized Cost Estimates

Capital cost estimates represent the total investment required to purchase and retrofit the control systems on existing storage tanks including the cost of cleaning and degassing tanks. Costs for research and development, lost time during installation and start-up, and other highly variable costs are not included in the estimates. These costs vary so widely from case to case and from situation to situation that it is virtually impossible to realistically quantify these costs. All capital costs reflect second quarter 1978 dollars.

Annualized control cost estimates include operating labor, maintenance, credits for petroleum savings, and annualized capital charges. Cost estimates were obtained from an EPA contractor, equipment vendors, tank service companies, local air pollution control reports, and an API contractor. Credits for gasoline savings due to emission control have been calculated from the emission reductions projected from the experimental tests.

The annualized capital charges are sub-divided into capital recovery costs (depreciation and interest costs) and costs for property taxes, insurance, and administration. Depreciation and interest costs have been computed using a capital recovery factor based on a 10 year secondary seal life and an interest rate of 10 percent per annum. Costs for property taxes, insurance and administration are computed at 4 percent of the capital costs. All annualized costs are for one year periods commencing with the second quarter of 1978.

4.2 CONTROL OF EMISSIONS FROM EXTERNAL FLOATING ROOF STORAGE TANKS

4.2.1 Model Cost Parameters

Cost parameters used in computing secondary seal control costs are presented in Table 4-2. These parameters are based on actual cost data from an oil industry journal,[2] a National Energy Information Center monthly publication,[3] an EPA contractor,[4] seal vendors,[5,6] tank service companies,[7,8] local air pollution control reports,[9,10] an API contractor,[11] and EPA estimates.

4.2.2 Control Costs

Table 4-3 shows the estimated costs of controlling VOC emissions from the model floating roof storage tank. The estimates pertain to existing welded and riveted floating roof petroleum liquids tanks that are equipped with primary closure seals. The installed capital costs are average industry costs of retrofitting a secondary seal on the model storage tank. The annual operating and maintenance costs are estimated based on normal maintenance and inspection programs. The annualized capital charges consist of the capital recovery costs using capital recovery factor with 10 percent annual interest rate and 10 year secondary seal life plus 4 percent of

Table 4-2. COST PARAMETERS USED IN COMPUTING CONTROL COSTS

I. Gasoline Value[a]

$100.60/m^3 ($16.00/bbl)

II. Secondary Seal Value:

A. Installed (Retrofit) Capital Costs:[b]

Tank with primary seal: $176 per linear m.

B. Annual Maintenance Cost:[c]

5% of installed capital cost plus annual inspection charge of $200.

C. Replacement Life:[d] 10 years

---

[a]Average gasoline value based on price data from Reference 2 and are shown in Table 4-5.

[b]Average installed cost of retrofitting secondary seal per References 4,5, 6,7,8,9 and 10.

[c]Annual maintenance cost per EPA estimate and annual inspection charge per Reference 12.

[d]Expected replacement life per References 4 and 8.

installed capital cost for property taxes, insurance and administration. The total annual control system costs are the sum of the annual operating and maintenance costs and annualized capital charges. Annual petroleum credits from controlling (reducing) emissions are not included in these costs.

From Table 4-3, it can be seen that the average installed capital cost of a secondary seal on a 30.5 m (100 ft) diameter tank is $16,900 and the total annual control system cost average is $4,400.

4.3 COST EFFECTIVENESS

Table 4-4 presents the cost effectiveness ratios of controlling gasoline emissions from the model existing floating roof tank. The $\$100.64/m^3$ price for gasoline was established by averaging the per barrel prices of regular, premium and no-lead gasoline from three different areas. The per barrel price was then converted to a $\$/m^3$. The cost effectiveness ratios for crude oil may be approximated by multiplying the cost effectiveness ratios in Table 4-4 by 1.38. For the development of this factor see Table 4-5. This factor reflects the different average values and emission rates of the two liquids. The amount of emissions controlled (reduced) varies with wind velocity, absolute vapor pressure and control efficiency. Higher wind velocity, greater vapor pressure and higher control efficiency will result in a greater quantity of controlled emissions and larger petroleum credits; opposite (low) values will result in a smaller quantity of emissions controlled and lesser petroleum savings. Since a range of the above controlling factors is needed to cover the typical range of tank operating conditions and locations, cost effectiveness ratios have been determined using various vapor pressure and wind velocity values for the factors and control system costs.

Table 4-3. CONTROL COST ESTIMATES FOR MODEL EXISTING GASOLINE STORAGE TANK

Facility Size:	30.5 m diameter (100 ft) 12.2 m height (40 ft) 8,910,000 liters capacity (55,000 bbl)		
Facility Type:	External Floating Roof Tank		
Control Device:	Rim Mounted Secondary Seal		
Type of Primary Closure Seal:	CASE I	CASE II	CASE III
Installed Capital Cost ($000):[a]	16.9	16.9	16.9
Annual Operating and Maintenance Cost ($000):[b]	1.1	1.1	1.1
Annualized Capital Charges ($000):[c]	3.3	3.3	3.3
Total Annual Control System Cost (Not including petroleum credits)($000):[d]	4.4	4.4	4.4

[a]Average installed cost of retrofitting secondary seal on existing floating roof tank per References 4,5,6,7,8, and 9.

[b]Annual operating and maintenance cost per EPA estimate and annual inspection charge per Reference 12.

[c]Capital recovery costs (using capital recovery factor with 10% annual interest rate, 10 year secondary seal life) plus 4% of installed capital cost for property taxes, insurance, and administration.

[d]Sum of annual operating and maintenance cost plus annualized capital charges; but, does not include petroleum credits (savings).

Table 4-4. COST EFFECTIVENESS OF CONTROLLING FLOATING ROOF GASOLINE STORAGE TANKS

	CASE I - WELDED TANK - PRIMARY SHOE SEAL, LIQUID-MOUNTED FOAM SEAL, LIQUID-MOUNTED LIQUID-FILLED SEAL											
Wind Velocity	9.7 kph				16.1 kph				22.5 kph			
True Vapor Pressure	13.8 kPa	27.6 kPa	41.4 kPa	69.0 kPa	13.8 kPa	27.6 kPa	41.4 kPa	69.0 kPa	13.8 kPa	27.6 kPa	41.4 kPa	69.0 kPa
VOC Emissions Controlled (Reduced) (Mg/yr)[a]	1.16	2.53	4.15	8.84	2.36	5.12	8.41	17.93	4.20	9.11	14.98	31.90
Annual Petroleum Savings (Credits) ($000/yr)[b]	(.17)	(.38)	(.63)	(1.33)	(.35)	(.77)	(1.26)	(2.69)	(.63)	(1.37)	(2.25)	(4.79)
Total Annual Control System Cost ($000/yr)	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4
Net Annual Cost (credit) ($000/yr)[c]	4.24	4.02	3.77	3.07	4.05	3.68	3.14	1.71	3.77	3.03	2.17	(.39)
Cost (credit) per Mg of Controlled Emissions ($/Mg)[d]	3655	1589	908	347	1716	709	373	95	898	333	145	(12)

	CASE II - WELDED TANK - PRIMARY FOAM SEAL VAPOR-MOUNTED											
Wind Velocity	9.7 kph				16.1 kph				22.5 kph			
True Vapor Pressure	13.8 kPa	27.6 kPa	41.4 kPa	69.0 kPa	13.8 kPa	27.6 kPa	41.4 kPa	69.0 kPa	13.8 kPa	27.6 kPa	41.4 kPa	69.0 kPa
VOC Emissions Controlled (Reduced) (Mg/yr)[a]	2.67	5.78	9.51	20.24	4.60	9.99	16.44	35.00	6.17	13.36	21.73	46.77
Annual Petroleum Savings (Credits) ($000/yr)[b]	(.40)	(.87)	(1.43)	(3.04)	(.69)	(1.50)	(2.47)	(5.25)	(.93)	(2.00)	(3.26)	(7.02)
Total Annual Control System Cost ($000/yr)	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4
Net Annual Cost (credit) ($000/yr)[c]	4.00	3.53	2.97	1.36	3.71	2.90	1.93	(.85)	3.47	2.40	1.14	(2.62)
Cost (credit) per Mg of Controlled Emissions ($/Mg)[d]	1498	611	312	67	807	290	117	(24)	562	180	52	(56)

Table 4-4 (continued). COST EFFECTIVENESS OF CONTROLLING FLOATING ROOF GASOLINE STORAGE TANKS

CASE III - RIVETED TANK WITH PRIMARY SHOE SEAL

Wind Velocity	9.7 kph				16.1 kph				22.5 kph			
True Vapor Pressure	13.8 kPa	27.6 kPa	41.4 kPa	69.0 kPa	13.8 kPa	27.6 kPa	41.4 kPa	69.0 kPa	13.8 kPa	27.6 kPa	41.4 kPa	69.0 kPa
VOC Emissions Controlled (Reduced) (Mg/yr)[a]	3.10	6.73	11.06	23.55	4.95	10.75	17.66	37.63	6.90	14.95	24.57	52.62
Annual Petroleum Savings (Credits) ($000/yr)[b]	(.47)	(1.01)	(1.66)	(3.53)	(.74)	(1.61)	(2.65)	(5.65)	(1.04)	(2.24)	(3.69)	(7.89)
Total Annual Control System Cost ($000/yr)	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4
Net Annual Cost (credit) ($000/yr)[c]	3.93	3.39	2.74	.87	3.66	2.79	1.75	(1.25)	3.36	2.16	.71	(3.49)
Cost (credit) per Mg of Controlled Emissions ($/Mg)[d]	1268	504	248	37	739	260	99	(33)	487	144	29	(66)

[a]Per Table 4-1.

[b](Emissions Before Control) x (VOC Control Efficiency) x (Recovered Petroleum Liquid Value) ÷ (Average Liquid Density)

[c]Sum of Annual Petroleum Savings (Credits) and Total Annual Control System Cost.

[d](Net Annual Cost (credit)) ÷ (VOC Emissions Controlled (Reduced)).

Table 4-5. FACTOR FOR ESTIMATING THE COST EFFECTIVENESS OF CONTROLLING CRUDE OIL STORAGE TANKS

	Gasoline	Crude Oil	Gasoline Cost Effectiveness Multiplyer
1. Molecular Weight of Emissions	65	50	1.300
2. Density of Condensed Emissions Kg/m^3 (lb/gal)	671 (5.6)	539 (4.5)	.804
3. Value of Product[a] $\$/m^3$ (\$/bbl)	100.6 (16.00)	76.21 (12.23)	1.320

Factor = (1) x (2) x (3) = (1.300)(.804)(1.320) = 1.3797 or 1.38.

[a]See References 2 and 3

For the model existing gasoline floating roof tank, it should be noted from Table 4-6 that the cost effectiveness ranges from a cost of $3,665 to a credit of $66 per Mg of controlled emissions. The corresponding cost effectiveness ratios of crude oil emission controlled using the 1.38 factor, vary from a cost of $5,044 to a cost of $25 per Mg. Thus, due to the higher value and emission rate of gasoline, the cost effectiveness for crude oil ranges from $66 to $1389 higher per Mg of controlled emissions than for gasoline.

4.4 ECONOMICS OF SCALE

The preliminary cost of retrofitting a secondary seal to existing floating roof tanks were also developed for a 10.7 m (35 ft) diameter tank and a 53.3 m (175 ft) diameter tank. These were developed to check the linearity of the scaling effect on cost effectiveness developed for our model tank. As could be expected there were some dis-economies of scale in the cost effectiveness of the smaller tank. This resulted in the smaller tank cost effectiveness ($/Mg of emissions controlled) being approximately 105 percent of the cost effectiveness of the 30.5 m (100 ft) diameter model tank. Also, as expected, the larger tank had some economies of scale. This resulted in the larger tank cost effectiveness ($/Mg of emissions controlled) being approximately 85 percent of the cost effectiveness of the 30.5 m (100 ft) diameter model tank.

Table 4-6. COST EFFECTIVENESS SUMMARY ($/Mg Controlled)

CASE	I			II			III		
Wind Velocity	9.7 kph	16.1 kph	22.5 kph	9.7 kph	16.1 kph	22.5 kph	9.7 kph	16.1 kph	22.5 kph
True Vapor Pressure									
13.8 kPa	3655	1716	898	1498	807	562	1268	739	487
27.6 kPa	1589	709	333	611	290	180	504	260	144
41.4 kPa	908	373	145	312	117	52	248	99	29
69.0 kPa	347	95	(12)	67	(24)	(56)	37	(33)	(66)

[a]Reference Table 4-4.

4.5 REFERENCES

1. "Methods for Extrapolating Chicago Bridge and Iron 6.1 M (20 Ft.) Test Tank Results to Full Size Tank," EPA-OAPQS Draft Report, April, 1978.

2. "Refined-products prices", Oil and Gas Journal, March 27, 1978

3. Monthly Energy Review, June 1978, Office of Energy Information and Analysis, National Energy Information Center.

4. R. Bakshi, Pacific Environmental Services, Inc., Santa Monica, Cal. Petroleum storage tank and seal cost data memo to file by R.A. Quaney, U.S. Environmental Protection Agency, dated November 2, 1977.

5. J. Hunter, Western Petro-Chemical Co., Los Angeles, Cal. Petroleum storage tank seal cost data memo to file by R.A. Quaney, U.S. Environmental Protection Agency, dated November 2, 1977.

6. K. J. Kolkmeier, Pittsburgh-Des Moines Steel Co., Pittsburgh, Pa. Petroleum storage tank seal cost data memo to file by R.A. Quaney, U.S. Environmental Protection Agency, dated November 2, 1977.

7. H.R. Wiggs, Tank Service, Inc., Tulsa, Oklahoma. Letter to R. H. Schippers, U.S. Environmental Protection Agency, dated May 18, 1977.

8. J. Mulkey, Tank Service, Inc., Wilmington, Del. Petroleum storage tank seal cost data memo to file by R.A. Quaney, U.S. Environmental Protection Agency, dated November 2, 1977.

9. California Air Resources Board. Public hearing - Proposed Ammendments to Rule 463 of SCAQMD, June 25, 1976.

10. California Air Resources Board. Public hearing - Proposed Ammendments to Rule 463 of SCAQMD, March 25, 1976.

11. Dr. W. Sheppard, Battelle Columbus Laboratories, Columbus, Ohio. Petroleum liquids transportation cost data memo to file by R.A. Quaney, U.S. Environmental Protection Agency, dated November 2, 1977.

12. R. H. Schippers, U.S. Environmental Protection Agency. Memo on Secondary Seals on New Petroleum Product Storage Tanks, dated May 25, 1977.

5.0 RECOMMENDED REGULATIONS, COMPLIANCE TEST METHOD, AND RECORD KEEPING

The affected facilities are external floating roof storage tanks with capacities greater than 150,000 liters (950 bbls) containing petroleum liquids with a true vapor pressure greater than 10.5 kPa (1.5 psi).

5.1 RECOMMENDED REGULATIONS

Recommended regulations for the storage of petroleum liquids in external floating roof tanks are:

1. Except where specifically exempted (See 5.1.4), all external floating roof tanks with capacities greater than 150,000 liters shall be retrofitted with a continuous secondary seal extending from the floating roof to the tank wall (a rim-mounted secondary) if:

(a) the tank is a welded tank, the true vapor pressure of the contained liquid is 27.6 kPa (4.0 psi) or greater, and the primary seal is one of the following:

(i) a metallic-type shoe seal, a liquid-mounted foam seal, or a liquid-mounted liquid-filled type seal, or

(ii) any other closure device which can be demonstrated equivalent to the above primary seals.

(b) the tank is a riveted tank, the true vapor pressure of the contained liquid is 10.5 kPa (1.5 psi) or greater, and the closure device is as described in 5.1.1 (a).

(c) the tank is a welded or riveted tank, the true vapor pressure of the contained liquid is $\geq$ 10.5 kPa (1.5 psi) and the primary seal is vapor-mounted. When such primary seal closure device can be demonstrated equivalent to the primary seals described in 5.1.1 (a), the provisions of 5.1.1 (a) apply.

2. The seal closure devices shall meet the following requirements:

(a) there shall be no visible holes, tears, or other openings in the seal(s) or seal(s) fabric.

(b) the seal(s) must be intact and uniformly in place around the circumference of the floating roof between the floating roof and the tank wall.

(c) the gap area of gaps exceeding 0.32 cm (1/8 inch) in width between the secondary seal installed pursuant to 5.1.1 (c) and the tank wall shall not exceed 6.5 cm^2 per 0.3 m of tank diameter (1.0 in^2 per foot of tank diameter).

3. All openings in the external floating roof, except for automatic bleeder vents, rim space vents, and leg sleeves, are to provide a projection below the liquid surface. The openings are to be equipped with a cover, seal or lid. The cover, seal or lid is to be in a closed position at all times except when the device is in actual use. Automatic bleeder vents are to be closed at all times except when the roof is floated off or landed on the roof leg supports and rim vents are to be set to open when the roof is being floated off the roof leg supports or at the manufacturer's recommended setting. Any emergency roof drain is to be provided with a slotted membrane fabric cover or equivalent cover that covers at least 90 percent of the area of the opening.

4. The following are specifically exempted from the requirements of 5.1.1:

(a) external floating roof tanks having capacities less than 1,600,000 liters (10,000 bbls) used to store produced crude oil and condensate prior to custody transfer.

(b) a metallic-type shoe seal in a welded tank which has a secondary seal from the top of the shoe seal to the tank wall (a shoe-mounted secondary).

(c) external floating roof tanks storing waxy, heavy pour crudes.

5. External floating roof tanks with a closure or other devices installed which will control VOC emissions with an effectiveness equal to or greater than the seals required in 5.1.1 (a).

5.2 COMPLIANCE TEST METHOD

1. Compliance for external floating roof tanks does not require measurement of the primary or secondary seal gap area, except as required to meet 5.1.2 (c), and can be determined by visual inspection.

2. For compliance with 5.1.2 (c), the secondary seal gap area can be determined by measuring the length and width of the gaps around the entire circumference of the secondary seal. Only gaps greater than or equal to 0.32 cm (1/8 inch) shall be used in computing the gap area. The area of the gaps can be accumulated to determine compliance.

5.3 MONITORING AND RECORD KEEPING

It is recommended that the routine visual inspections be conducted annually or at shorter intervals, and that the secondary seal gap measurements be made annually. Evidence of any type of malfunction (as noted above) is to be recorded.

When a liquid having a true vapor pressure greater than 7.0 kPa (1.0 psi) is stored in an external floating roof tank not equipped with a secondary seal or approved alternative control technology (see 5.1.5), a record should be maintained for no more than two years of the average monthly storage temperature, the type of liquid, and the Reid vapor pressure of the liquid.

The true vapor pressure may be determined by using the average monthly storage temperature and typical Reid vapor pressure of the contained liquid or from typical available data on the contained liquid. Supporting analytical data can be requested if there is a question on the values reported.

APPENDIX A

SELECTION OF EXPERIMENTAL TESTS FOR WIND INDUCED EMISSION CALCULATIONS

An experimental 20' Ø test tank at the Plainfield, Illinois, Research Center of Chicago Bridge and Iron Company (CBI) has been extensively used by industry to investigate the mechanisms causing hydrocarbon emissions from floating roof tanks.[1,2,3,4,5,6] A large number of tests were conducted on various types of seals to study the effect of parameters such as wind speed, gap between the seal and tank wall, and the leak rate of the shoe seal vapor space system on hydrocarbon emissions. Secondary seal efficiency was evaluated. Methods for extrapolating specific test results from the 20' Ø test tank to full size tanks have been developed. This appendix describes the methodology used in selecting specific tests for extrapolation which are considered representative of average field tank conditions.

A. METHODOLOGY OF SELECTION

The selection of CBI tests on primary seals which represent the "average" primary seal gap in the field was based on EPA's analysis of tank inspections made in 1976 by regulatory agencies in California. A total of 398 tanks were included in this analysis; 163 welded tanks with primary shoe seals, 141 welded tanks with non-metallic seals of either the foam or liquid type, and 94 riveted tanks with shoe seals. Tanks equipped with a weather guard over the primary seal were included. Excluded were 47 tanks which were reported to have either a "double" or "wiper" secondary seal.

In the inspections, gaps between the primary seal and tank wall were measured with probes or rods of varying dimensions. The width and length of each gap was recorded. It was not possible to derive from the inspection data an average gap width in the field that was comparable to a specific CBI test, nor a range of gap width patterns which could be compared to one or several CBI tests.

The final selection was made by comparing the gap areas in the tanks inspected to the gap area in the CBI tests expressed as in^2 /ft of tank diameter.

B. SELECTION OF WELDED TANK WITH SHOE SEAL AND RIM-MOUNTED SECONDARY SEAL

A number of tests were made with single shoe seals having gaps up to 1 1/2 inches simulated by forcing the primary seal away from the tank wall with spacer bar arrangements.[7,8,9] In all of these tests the leakage rate for the seal system (the space bounded by the shoes, the envelope, the rim space and liquid) averaged about 0.032 SCFM per foot of tank diameter at 1 1/2 inches of H_2O pressure drop. A leakage rate of 0.50 SCFM at 1.5 inches of H_2O is considered commercially achievable. Further research was conducted by CBI to establish the relationship between shoe seal emissions and leak rate. The leak rate of seals inspected in California is unknown. The final determination of the base case for calculating wind induced emissions for a primary shoe seal was made by; (1) using the methodology described in (A), and (2) using a test that simulated a leak rate of 0.8 SCFM/ft of tank diameter at 1.5 inches of H_2O pressure drop. This leak rate appears reasonable based on field test data and the California inspections which revealed relatively few tanks with openings or tears in the envelope.

A comparison of the gap area in the inspected tanks with specific CBI tests is shown in Table A-1. Selected tests on envelope leak rate simulations are also shown in this table.

It will be noted from Table A-1 that 89 percent of the tanks had gap areas (in^2/ft tank diameter) equivalent to tests where emissions remained relatively unchanged from a shoe seal with a tight commercial fit to one having a gap(s) up to one inch.

Test W-12 has a commercial fit and simulates a seal system vapor space leak rate of 0.8 SCFM per ft of tank diameter at 1.5" H_2O. W-12 was selected as the base case for wind induced emission calculations.

A rim-mounted secondary over the W-12 primary seal was then judged to have at least a 75 percent efficiency based on numerous secondary seal single seal combinations tested with varying gaps in the primary, secondary, or both, during the same test.

C. WELDED TANK WITH SHOE SEAL AND SHOE-MOUNTED SECONDARY SEAL

A secondary wiper seal mounted on the shoe was tested with a tight commercial fit and with gaps.[10] The efficiency of the wiper in each of these tests was used to estimate the base case (test W-12) emission reductions.

D. RIVETED TANK WITH A SHOE SEAL AND RIM-MOUNTED SECONDARY

Test W-28 was made with a single shoe seal in contact with simulated horizontal and vertical rivet rows.[11] Table A-2 gives a comparison of the gap area in the inspected tanks and the gap area in this test configuration. The gap area in a riveted tank will vary with the position of the roof in the tank and the rivet patterns in W-28 represent a condition where gaps may be expected to be at maximum. This is judged to be the reason why the inspected

TABLE A-1. SEAL GAP AREA IN INSPECTED WELDED TANKS WITH SHOE-SEAL COMPARED TO CBI EXPERIMENTAL TESTS

20 Ft. Diameter Experimental Test Tank							Tanks Inspected	
		Gaps in Seal						
Test No.	Envelope Leakage SCFM/ft Dia. at 1.5" H_2O	No	Width (inch)	Total Area[b] (inch ^{2})	Inch ^{2} per Ft. Tank Dia.	Emissions[a] (lbs/day)	Number	Percent
W1,W1R,W2,V3	0.032	0[b]	0	0	0	6.2	14	8.6
W-3	0.032	2	1/2	35	1.75	6.2	93[c]	57.1
W-5	0.032	2	1	86	4.30	6.2	38[d]	23.3
W-6	0.032	1 (½ tank circ.)	1/2	187	9.35	17.0	12[e,h]	----[h]
W-26	0.0085	4	1-1/2	294	14.70	7.4	6[f,g]	11.0[h]
						TOTAL	163	100.0
W-12	0.80	0	0	0	0	7.3		
W-17	1.50	0	0	0	0	14.0		
W-16	2.80	0	0	0	0	16.0		
W-15	4.50	0	0	0	0	25.0		

[a] Vapor pressure - 5 psia, wind speed - 10 mph.

[b] Includes area of tapers

[c] > 0 $\bar{<}$ 1.75 in ^{2}/ft tank diameter

[d] > 1.75 $\bar{<}$ 4.3 in ^{2}/ft tank diameter

[e] > 4.3 $\bar{<}$ 9.35 in ^{2}/ft tank diameter

[f] > 9.35 $\bar{<}$ 14.7 in ^{2}/ft tank diameter

[g] Includes only one tank > 14.7

[h] Continuous gaps this magnitude not recorded in inspections; these tanks are included in W-26 (%).

TABLE A-2. SEAL GAP AREA IN INSPECTED RIVETED TANKS WITH SHOE SEALS COMPARED TO CBI EXPERIMENTAL TESTS

20 Ft. Diameter Experimental Test Tank							Tanks Inspected	
Test No.	Envelope Leakage SCFM/ft Dia. at 1.5" H_2O	Gaps in Seal: No	Width (inch)	Total Area ($inch^2$)	$Inch^2$ per Ft. Tank Dia.	Emissions[a] (lbs/day)	Number	Percent
W-28		Continuous at:						
		(a) Top of Shoe	1.05	791	39.5	} 26.0	0	0
		(b) Bottom of Shoe	0.50	376	18.3			
		Gaps in Inspected Tanks:			0		0	0
					$\geq 0 \leq 1.75$		38	40.4
					$\geq 1.75 \leq 4.3$		40	42.6
					$\geq 4.3 \leq 9.4$		13	13.8
					$\geq 9.4 \leq 18.3$		3	3.2
						TOTAL TANKS	94	100.0

[a]Vapor pressure - 5 psia; wind speed - 10 mph

[b]Gaps more numerous and approaching continuity in many cases - more similar to W-6 Table A-1.

gap areas, taken at random roof positions, are considerably lower than W-28. The inspected gap areas in the riveted tanks are substantially greater than in the welded tanks in Table A-1. Also, the numbers of gaps in the riveted tanks were far more numerous than in the welded tanks and gaps in riveted tanks may exhibit the characteristics of the continuous gap in test W-6.

A rim-mounted secondary over W-28 was tested in contact with two rivet patterns, tests W-29 and W-31. Emissions were calculated for both these tests and reductions obtained by subtraction from W-28.

E. RESILIENT FOAM SEAL MOUNTED IN RIM VAPOR SPACE OF WELDED TANK

Two tests were selected for the single seal. A single seal test with a "tight commercial fit" (Test 13, 16, 20, 21) and the same seal with gaps (Test 23).[12,13]

A rim-mounted secondary with a "tight commercial fit" was installed in each of the above tests. Emissions were then calculated for each (Test 32 and 34A) and emission reduction obtained by difference.

Inspection data for "non-metallic" seals are presented in Table A-3. The seals were not identified by type (liquid filled or foam) or location (rim vapor space or in the liquid surface).

For comparative purposes emissions were developed for a secondary seal with gaps (Test 34B) installed over a primary seal with gaps (Test 23).

TABLE A-3. SEAL GAP AREA IN INSPECTED WELDED TANK WITH NON-METALLIC SEALS[a] COMPARED TO CBI EXPERIMENTAL TESTS

20 Ft. Diameter Experimental Test Tank						Tanks Inspected	
	Gaps in Seal						
Test No.	No	Width (inch)	Total Area ($inch^2$)	$Inch^2$ per Ft. Tank Dia.	Emissions[b] (lbs/day)	Number	Percent
13,16,20,21	0	0	0	0	12.1	71	64.5
23	2	1/2	24	1.2	> 98.0[b]		
Inspected Tanks with Gaps:							
				$\geq 0 \leq 0.5$		19	17.3
				$\geq 0.5 \leq 1.2$		10	9.1
				> 1.20		10	9.1
SUBTOTAL (WITH GAPS)						39	35.5
TOTAL TANKS						110	100.0

[a]Unable to identify as to type or if mounted in vapor space or on liquid surface.

[b]Vapor pressure - 5 psi ; wind speed - 10 mph.

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1. SOHIO/CBI Floating Roof Emission Program, Interim Report, October 7, 1976.

2. SOHIO/CBI Floating Roof Tank Emission Program, Final Report, November, 1976.

3. Western Oil and Gas Association, Metallic Sealing Ring Emission Test Program, Interim Report, Chicago Bridge & Iron Company, January, 1977.

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8. Reference 4, Op. Cit.

9. Reference 2, Op. Cit.

10. Reference 6, Op. Cit.

11. Reference 4, Op. Cit.

12. Reference 1, Op. Cit.

13. Reference 2, Op. Cit.

APPENDIX B

CALCULATION OF WIND INDUCED EMISSIONS FROM EXPERIMENTAL TESTS

A. EQUATION FOR WIND INDUCED EMISSIONS

Emissions were extrapolated from the 20' Ø test tank selected tests to the 100' Ø model gasoline storage tank using the following equation:[1,2,3]

$$E_F = 1.2337 \times 10^{-4} \times \left[\frac{P_F}{[1 + (1 - .068\ P_F)^{.5}]^{2.0}} \right] \times D_F \times M_{HC} \times E_P$$

Where:

E_F = Emissions from full size tank, megagrams/yr

E_P = Emissions from test tank at 5.0 psi, lbs/day

P_F = Vapor pressure of stored product in full size tank, psi

D_F = Diameter of full size tank, feet = 100

M_{HC} = Molecular weight of full size tank hydrocarbon emissions (hydrocarbon vapor molecular weight), lbs/lb mole = 65

B. E_P FOR THE TEST TANK

In each specific test emissions were measured at varying simulated wind speeds. These results were then plotted to yield a smooth "E_P vs Windspeed" curve for each test.[4] E_P values for the selected tests and various wind speeds read from these plots are given in Table B-1.

In the 100' Ø model tank analysis wind speeds of 6 mph, 10 mph, and 14 mph were used. These represent mean average annual wind speeds on the West Coast, Gulf Coast and East Coast, respectively.

TABLE B-1 - E_p (lbs/day) vs Wind Speed (mph)
(20' Ø Test Tank - 5.0 psi)

Selected Tests	Wind Speed (mph)					
	4	6	8	10	12	14
Welded Tank - Shoe Seal						
Single Seal (W-1, W-2 W-1R)	1.80	3.10	4.60	6.20	7.60	9.20
Single Seal (W-12)	2.10	3.60	5.20	7.30	10.00	13.00
Rim-Mounted Secondary (25 % W-12)	0.53	0.90	1.30	1.83	2.50	3.25
Shoe-Mounted Secondary Tight Fit (G-2)	0.92	1.40	1.87	2.35	2.80	3.30
Shoe-Mounted Secondary Gaps (C-1)	1.60	2.00	3.12	3.80	4.60	5.30
Riveted Tank - Shoe Seal						
Single Seal (W-28)	10.10	16.00	21.0	26.0	32.0	36.0
Rim-Mounted Secondary (W-29)	5.90	8.80	11.8	14.5	17.3	20.0
Rim-Mounted Secondary (W-31)	1.88	2.80	3.75	4.60	5.70	6.40
Welded Tank - Foam Seal In Rim Vapor Space						
Single Seal (13,16,20, 21)	3.70	7.00	9.8	12.1	15.0	17.0
Single Seal (23)	26.0	62.0	98.0	>98		
Rim-Mounted Secondary (34A)	0.70	1.10	1.80	2.80	4.20	6.00
Rim-Mounted Secondary (32)	0.62	0.82	1.05	1.41	2.0	2.70
Rim-Mounted Secondary (34B)	1.70	4.20	12.0	62.0	>62.0	

C. EMISSION CALCULATIONS

C.1 Primary Seal With and Without Rim-Mounted Secondary

Using the equation in (A) emissions were calculated for each of the selected tests at wind speeds of 6 mph, 10 mph and 14 mph, and stored gasoline vapor pressures of 2 psi, 4 psi, 6 psi and 10 psi. Emissions reductions are the difference between the single seal case (base case) and secondary seal case (control case). The results for a model 100' Ø tank storing gasoline whose hydrocarbon emissions have a molecular weight of 65.0 lbs/lb mole are given in Table B-2.

C.2 Shoe Seal With Shoe-Mounted Secondary

The shoe mounted secondary was tested on a primary shoe seal with a vapor space leak rate of < 0.1 SCFM per ft of tank diameter (Tests C-1, C-2, and W-1R). Emissions controlled in Test C-1 and C-2 were calculated at various wind speed and vapor pressure parameters. The emissions controlled were then subtracted from the emissions in the base case, Test W-12, to determine emissions from a shoe mounted secondary. The results are given in Table B-3.

TABLE B-2 - EMISSIONS FROM 100' Ø GASOLINE TANK (MEGAGRAMS/YR)

Wind Speed - MPH		6				10				14			
Stored Product Vapor Pressure-PSIA		2	4	6	10	2	4	6	10	2	4	6	10
Experimental Test	Test Number												
Welded Tank-Shoe Seal													
Single Seal	W-12	1.55	3.36	5.53	11.78	3.15	6.82	11.22	23.90	5.60	12.15	19.98	42.54
Rim Mounted Secondary	(25% W-12)	0.39	0.83	1.38	2.94	0.79	1.70	2.81	5.97	1.40	3.04	5.00	10.64
ΔEmissions[a]		1.16	2.53	4.15	8.84	2.36	5.12	8.41	17.93	4.20	9.11	14.98	31.90
Shoe Mounted Secondary	Adj.C-2 (See Table 3)	0.81	1.77	2.91	6.22	1.49	3.22	5.30	11.30	3.06	6.64	10.90	23.24
ΔEmissions		0.74	1.59	2.62	5.66	1.66	3.60	5.92	12.60	2.54	5.51	9.08	19.30
Shoe Mounted Secondary	Adj.C-1 (See Table 3)	1.07	2.33	3.84	8.18	2.12	4.58	7.53	16.04	3.92	8.51	13.98	29.78
ΔEmissions		0.48	1.03	1.69	3.60	1.03	2.24	3.69	7.86	1.68	3.64	6.00	12.76
Riveted Tank-Shoe Seal													
Single Seal	W-28	6.89	14.95	24.59	52.35	11.20	24.29	39.95	85.07	15.51	33.63	55.32	117.70
Rim Mounted Secondary	W-29	3.79	8.22	13.53	28.80	6.25	13.54	22.29	47.44	8.61	18.68	30.75	65.44
ΔEmissions[a]		3.10	6.73	11.06	23.55	4.95	10.75	17.66	37.63	6.90	14.95	24.57	52.62
Rim Mounted Secondary	W-31	1.21	2.62	4.31	9.16	1.98	4.30	7.07	15.05	2.76	5.98	9.84	20.94
ΔEmissions		5.78	12.33	20.28	43.19	9.22	19.99	32.88	70.02	12.75	27.65	45.48	96.76
Welded Tank-Resilient Foam Seal in Rim Vapor Space													
Single Seal (with no gaps)	13,16,20,21	3.02	6.54	10.76	22.90	5.21	11.30	18.60	39.59	7.33	15.88	25.88	55.60
Secondary Seal (no gaps)	32	0.35	0.76	1.25	2.66	0.61	1.31	2.16	4.59	1.16	2.52	4.15	8.83
ΔEmissions[a]		2.67	5.78	9.51	20.24	4.60	9.99	16.44	35.00	6.17	13.36	21.73	45.77
Single Seal (with gaps)	23	26.72	57.91	95.27	202.9	59.64[b]	129.38[b]	212.79[b]	453.5[b]	-	-	-	-
Secondary Seal (no gaps)	34A	0.47	1.03	1.69	3.60	1.21	2.62	4.31	9.16	2.59	5.60	9.23	19.63
ΔEmissions		25.25	56.88	93.58	199.3	58.43	126.76	208.48	444.34	-	-	-	-
Secondary Seal with Gaps Over Primary Seal with Gaps	34B	1.81	3.92	6.46	13.74	26.72	57.91	95.33	202.87	-	-	-	-

a Emission Reduction used in Chapter 4.0
b Extrapolated

TABLE B-3 - EMISSIONS FROM 100' Ø WELDED GASOLINE TANK WITH SHOE MOUNTED SECONDARY SEAL (MEGAGRAMS/YR)

Wind Speed - MPH		6				10				14			
Stored Product Vapor Pressure-PSIA		2	4	6	10	2	4	6	10	2	4	6	10
Experimental Test	Test Number												
Shoe Mounted Secondary-Tight Fit													
Base Case: Shoe Seal with Leak Tight Envelope	W1, W1R, W2	1.34	2.90	4.77	10.14	2.67	5.79	9.53	20.29	3.96	8.59	14.15	30.10
Base Case with Shoe Mounted Secondary	C-2	0.60	1.31	2.15	4.58	1.01	2.19	3.61	7.69	1.42	3.08	5.07	10.80
Controlled by Secondary		0.74	1.59	2.62	5.56	1.66	3.60	5.92	12.60	2.54	5.51	9.08	19.30
Shoe Seal with Envelope Leak Rate 0.8 SCFM/ft Tank Ø - 1 1/2" H_2O	W-12	1.55	3.36	5.53	11.78	3.15	6.82	11.22	23.90	5.60	12.15	19.98	42.54
Controlled by Secondary		0.74	1.59	2.62	5.56	1.66	3.60	5.92	12.60	2.54	5.51	9.08	19.30
Shoe Seal with Shoe Mounted Secondary	Adjusted C-2	0.81	1.77	2.91	6.22	1.49	3.22	5.30	11.30	3.06	6.64	10.90	23.24
Shoe Mounted Secondary-With Gaps													
Base Case: Shoe Seal with Leak Tight Envelope	W1, W1R W2	1.34	2.90	4.77	10.14	2.67	5.79	9.53	20.29	3.96	8.59	14.15	30.10
Base Case with Shoe Mounted Secondary	C-1	0.86	1.87	3.08	6.54	1.64	3.55	5.84	12.43	2.28	4.95	8.15	17.34
Controlled by Secondary		0.48	1.03	1.69	3.60	1.03	2.24	3.69	7.86	1.68	3.64	6.00	12.76
Shoe Seal with Envelope Leak Rate 0.8 SCFM/ft Tank Ø - 1 1/2" H_2O	W-12	1.55	3.36	5.53	11.78	3.15	6.82	11.22	23.90	5.60	12.15	19.98	42.54
Controlled by Secondary		0.48	1.03	1.69	3.60	1.03	2.24	3.69	7.86	1.68	3.64	6.00	12.76
Shoe Seal with Shoe Mounted Secondary	Adjusted C-1	1.07	2.33	3.84	8.18	2.12	4.58	7.53	16.04	3.92	8.51	13.98	29.78

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1. Summary of 20 foot Diameter Pilot Floating Roof Hydrocarbon Emission Test Results, Chicago Bridge & Iron Company, December 28, 1977.

2. Hydrocarbon Emission Loss Measurements on a 20' Ø Floating Roof Tank with a Type SR-1 Seal for a Product at Various Vapor Pressures, Chicago Bridge & Iron Company, October 25, 1977.

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4. Reference 1, Op Cit.

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16. ABSTRACT

This report provides the necessary guidance for development of regulations limiting emissions of volatile organic compounds (VOC) from storage of petroleum liquids in external floating roof tanks. Reasonably available control technology (RACT) is defined in this document; cost analysis for RACT is included for evaluating the cost effectiveness of controlling external floating roof tank sources.

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