DRAFT REPORT

Submitted by:

Pope-Reid Associates, Inc.
245 E. 6th Street, Suite 813
St. Paul, MN 55101

APPENDIX A

PROBABILITY AND RELEASE VOLUME CALCULATIONS

A.0 INTRODUCTION

This appendix consists of two parts: the derivation of formulas used throughout the failure analysis, and the documentation of the failure probabilities and leak rates used for the individual failure events. The general derivations are presented on pages A-2 through A-11. The individual failure events are discussed in the remainder of this Appendix.

A.1 GENERAL DERIVATIONS

The following computations were common to many of the failure events:

- Calculation of release rates from underground leaks (fluid bed model);
- Calculation of release rates into an air environment (Bernoulli flow);
- Conversion from hydraulic head to pressure;
- Computation of fluid velocity in pipes;
- Determination of pressure of flowing liquid in pipes; and
- Calculation of fill/discharge times.

These calculations are described in the following pages.

A.1.1. Underground Releases (for leaks that are impeded by soil or backfill)

EQUATIONS:

- We calculated underground leak rates using the Ergun equation for the pressure drop in beds of mixed particles (Source: Fluidization Engineering, Daizo Kunii and Octave Levenspiel, p. 70 (1969)). This equation is:

$$\frac{\Delta P}{L} g_c = 150\left(\frac{(1-E_m)^2}{E_m^3}\right)\left(\frac{\mu u_o}{(\phi_s d_p)^2}\right) + \left(\frac{1.75\ (1-E_m)}{E_m^3}\right)\left(\frac{\rho u_o^2}{\phi_s d_p}\right)$$

where

P = the pressure drop across the bed

E_m = the void fraction for the particles

μ = viscosity

u_o = velocity of flow

ϕs = sphericity of the particles

ρ = density of fluid

d_p = average particle size

g_c = 1 in metric units

L = the dispersion length

- This is a quadratic equation in u_o. Thus,

$$u_o = \frac{-B + (B^2 - 4AC)^{.5}}{2A}$$

where $A = \left(\frac{1.75(1-E_m)}{E_m^3}\right)\left(\frac{\rho}{\phi_s d_p}\right)$

$B = \frac{150(1-E_m)^2}{E_m^3\ (\ _s d_p)^2}$

$C = \left(\frac{-\ \Delta P}{L}\right) g_c$

- The leak rate is simply

$$dQ/dt = u_0 A$$

- L for fluid beds is approximately 4 to 5 bed diameters. (Source: R. H. Perry and C. H. Chilton, Chemical Engineers' Handbook, 5th Ed (1973), pp. 5-49). The underground leaks studied in this model, however, involve conical dispersion patterns, rather than the cylindrical fluid beds considered by Perry and Chilton. In addition, L will also vary with the dispersion characteristics of the surrounding backfill. After extensive analysis and sample calculations, we have chosen the following dispersion lengths:

	Backfill Material			
	Clay	Silt	Sand	Gravel
Circular holes				
(usual value)	2d	7.5d	20d	100d
(maximum permissible)	2 cm	7.5 cm	20 cm	100 cm
Cracks				
(usual value)	4 w	20 w	40 w	100 w
(maximum permissible)	4 cm	20 cm	40 cm	100 cm

where:

d is the hole diameter, and
w is the crack width

- Additional parameters are as follows:

	Backfill Material			
	Clay	Silt	Sand	Gravel
void fraction	0.95	0.75	0.53	0.50
particle size (mm)	0.002	0.064	0.25	9.4
sphericity	0.075	0.34	0.65	0.70

USER INPUTS:

- Pressure
- Area of hole
- Density of liquid
- Viscosity of liquid
- Soil characteristics
- Type of hole (circular or crack)
- Diameter or width of hole

A.1.2. Bernoulli Flow (into an air environment)

EQUATIONS:

- This calculation applies to leaks that are unimpeded by soil resistance.
- The loss rate can be calculated by a simple application of Bernoulli's equation for a sharp-edged orifice.
- $dQ/dt = .6A\ (2gz)^{.5}$

  where

  dQ/dt = leak rate

  A = area of hole

  g = acceleration due to gravity

  z = height of liquid

USER INPUTS:

- Hydraulic head
- Area of hole

COMMENTS:

- The flow through small holes under relatively low pressure is turbulent, as can be verified by calculating a typical Reynold's number. The Reynolds number for loss through a (1/32)" hole for methylene chloride under 2 feet of head is 7500. This is in the upper end of the transition zone between turbulent and laminar flow. Use of Poiseville's Equation for laminar flow gives a considerably higher flow rate, so turbulent flow will be assumed.

A.1.3. Conversion from hydraulic head to pressure

EQUATIONS:

- Some equations in this Appendix use ΔP (pressure drop). Others call for z (hydraulic head). These two quantities are related by the following formula:

$$\Delta P = \rho(g/g_c)z$$

where

ρ = density of fluid

g = acceleration due to gravity

g_c = a conversion factor which is 1 in metric units and 32.17 in English units

USER INPUTS:

- Hydraulic head or pressure drop
- Density of fluid

A.1.4. Fluid velocity in pipes

EQUATIONS:

- For flowing fluid in a pipe, the following energy balance equation applies (Source: M. S. Peters and K. D. Timmerhaus, Plant Design and Economics for Chemical Engineers, 3rd Ed (1980) pp. 509-515):

$$\frac{P_1}{\rho \frac{g}{g_c}} + \frac{V_1^2}{2g} + z_1 = \frac{P_2}{\rho \frac{g}{g_c}} + \frac{V_2^2}{2g} + z_2 + h_s + h_f$$

where

P_1 = inlet pressure

ρ = density

g = acceleration of gravity

g_c = a conversion factor (1 in metric units, 32.17 in English units

V_1 = inlet velocity

z_1 = inlet elevation above arbitrary base

P_2 = outlet pressure

V_2 = outlet velocity

z_2 = outlet elevation

h_s = hydraulic head added by the pump

h_f = frictional losses (measured as loss of hydraulic head)

- F is composed of 3 parts: losses at entrance to pipe, losses along the pipe, losses at pipe exit.
- The following frictional loss equations apply to these losses (Source: Peters and Timmerhaus)

sudden enlargement

$$F_e = \frac{(V_1-V_2)^2}{2ga} \qquad a = 1 \text{ (turbulent flow)}$$

sudden contraction

$$F_c = \frac{K_c V_2^2}{2ag}$$

$a = 1$
K_c = .05 for large diameter-changes

pipes and pipe elbows

$$F = \frac{2fv^2(L_e + L)}{gD}$$

f = friction factor = 5×10^{-3} for turbulent flow

L = length of straight pipe

L_e = effective length of elbows

D = diameter of pipe

- For systems open to the atmosphere $P_1 = P_2 = 1$ atm
- For large inlet tanks, $V_1 = 0$
- Set $z_1 = 0$
- Then

$$V_2^2 = 2g\,(-z_2 - h_s - h_f)$$

V_2^2 also appears in h_f, so

$$V_2^2 = -(z_2 + h^s)\left(\frac{1}{2g} - \frac{1}{2g} + \frac{1}{4g} + \frac{10^{-2}(L_e + L)}{gD}\right)^{-1}$$

$$= -(z_2 + h_s)\left(\frac{1}{4g} + \frac{10^{-2}(L_e + L)}{gD}\right)^{-1}$$

A.1.5. Pressure of flowing liquid in pipes

EQUATIONS:

- Pressure in a pipe is given by solving the energy balance equation in Section A.1.4 for P_2. Hence:

$$P_2 = P_1 - \left(\rho \frac{g}{g_c}\right)\left(\frac{V_2^2}{2g} + z_2 + h_s + h_f\right)$$

where $V = V_2$ = velocity of flow

- The pressure difference between the pipe interior and the pipe exterior is given by $\Delta P = P_2 - P_1$. Thus:

$$\Delta P = -\left(\frac{g\rho}{g_c}\right)\left(\frac{V_2^2}{2g} + z_2 + h_s + h_f\right)$$

- At the midpoint of the pipe, the friction losses include only losses from the inlet and half of the effective pipe length. Hence, at the midpoint of the pipe:

$$h_f = F_c + \frac{1}{2} F$$

$$= \frac{.05V^2}{2g} + \frac{5 \times 10^{-3}\ V^2(L_e + L)}{gD}$$

- Thus, substituting this equation in the preceding equation gives:

$$\Delta P = \left(\frac{-\rho}{g_c}\right)\left(\frac{V^2}{2} + \frac{.05V^2}{2} + \frac{5 \times 10^{-3}\ (L_e + L)V^2}{D} + gz_2 + gh_s\right)$$

$$\Delta P = \left(\frac{-\rho}{g_c}\right)\left(.525V^2 + \frac{5 \times 10^{-3}\ (L_e + L)V^2}{D} + gz_2 + gh_s\right)$$

A.1.6. Fill/discharge time

EQUATIONS:

- The length of time necessary for tank filling or discharge can be calculated from the fluid velocity in the pipe, the pipe diameter, and the volume to be transferred:

$$T = Q/ \pi r^2 v$$

where

Q = transfer volume
r = inside radius of pipe
v = velocity of flow

USER INPUTS:

- Transfer volume
- Velocity of flow (from Section A.1.4)
- Pipe diameter (interior)

A.2 FAILURE DATA SHEETS

The following data sheets discuss the probabilities and release volumes for individual fault tree events.

The events discussed in these data sheets generally represent individual fault tree events, but there is not always a one-to-one correspondence. When it facilitates discussion, we have sometimes combined similar events. In addition, we have occasionally divided our discussion of single fault-tree events in order to focus more clearly on the differences between various tank designs or operating conditions. These changes in the fault tree event classifications have been clearly labeled.

For these reasons, it is not appropriate to read one data sheet without also becoming familiar with the data sheets for similar events. Important caveats may apply to a whole series of events, but in order to focus on the differences among related events, all similarities are not necessarily re-stated. Liberal cross-references have been supplied, but they are not a substitute for a careful reading of the related data sheets.

The labels for the events described in these data sheets may be confusing to the first-time reader. Therefore, the following guide may be useful:

Label Prefix	Category of Event Depicted
Txxxx	Tank defects (corrosion, rupture, etc.)
B1x	Piping, flanges, and gaskets
B2x - B6X	Secondary-containment devices
A1111x	Spills during discharge
A21x	Release routes for overflows (corroded vent pipe, corroded flanges, open-topped tank, etc.)
ANUCAT (I, x)	Catastrophic events (flood, fire, etc.)
LIFDEF (I, x)	Lifetime defects (improper installation, damage during installation, etc.)

xxxxxx	Miscellaneous events (including overfill, operator error, alarm failure, level gauge failure, etc.) These are listed in alphabetical order.

It may also be useful to summarize a few items of commonly-occurring notation:

Notation	Explanation
p	Binomial probability.
N(x,y)	Normal distribution with mean of x, standard deviation of y.
pN(x,y)	Conditional normal distribution. p is the binomial probability that failure occurs; N(x,y) is the distribution of times to failure given that failure does occur.
FNU(x,y)	A uniform distribution between x and y.
Maximum = y	Unless a minimum is also specified, this means FNU(0,y).
B(a,b,c)	Beta distribution with minimum value a, mode b, and maximum c.

These explanations should make the event sheets more accessible to the general reader.

LABEL: T1121

FAILURE: Localized exterior corrosion

SOURCES: Petroleum Association for Conservation of the Canadian Environment, "Underground Tank Systems: Review of State of the Art and Guidelines," PACE Report No. 82-3, Ottawa (1983).

CALCULATIONS:

- The PACE data are presented and analyzed in Appendix C.
- The results of that analysis are cumulative time-to-failure distributions for each of 3 categories of Soil Aggressiveness Values (SAV's). (SAV's are discussed in Appendix C).

Cumulative Probability of Failure

Tank Age	Low SAV (0-6)	Medium SAV (7-12)	High SAV (< 13)
4	0	0	0
9	0	11.1	26.7
14	6.3	29.1	49.9
19	24.0	54.0	76.5
24	48.3	67.3	79.9
30[1]	69.9	76.6[2]	83.3

[1] This age has been chosen as representative of the $\geq$ 25 bracket.

[2] A probability for this category could not be calculated from the raw data. In order to complete the table, this number was obtained by averaging 69.9 and 83.6. It appears to be a reasonable value.

PROBABILITY DISTRIBUTION: Empirical

PROBABILITY: See above table.

DATE OF INITIAL RELEASE:

- SAV must first be calculated as shown in Appendix C. This will require the following inputs:
  - Soil resistivity (ohm-cm)
  - Soil pH
  - Soil moisture

- Presence or absence of sulfides
- Differential characteristics

- The failure date may now be sampled from the probability table.

- A corrosion rate may be obtained by dividing the resulting failure date by the average tank wall thickness for the tanks in the PACE survey. This thickness is assumed to be .25 inches.

- The date of failure will be the date at which the sum of accumulated local external corrosion plus general internal corrosion reaches the initial wall thickness of the tank in question. (General internal corrosion is calculated under event T1125). General exterior corrosion does not enter into this analysis, for we assume that it is already included in the corrosion rate for localized exterior corrosion. In addition, localized interior corrosion is not included in this analysis, for it is unlikely that localized internal and external corrosion will occur at the same point on the tank wall. Thus, it is unlikely that pits from these two causes will "meet in the middle."

MATERIALS AND CONFIGURATION VARIATIONS:

- The PACE-derived probability distribution is assumed to apply only to unprotected steel tanks.

- Material changes, use of cathodic protection, and use of coatings will alter corrosion probabilities and hence dates of failure. These effects are summarized in the following table:

Tank design	Effect on probability of failure
Carbon steel (underground, unprotected)	PACE baseline
Carbon steel (underground, coated)	Delays onset of corrosion by N(7,3) years, then corrosion becomes a certainty. Time-to-failure distribution is given below.
Carbon steel (above-ground, unprotected)	Corrodes like underground tank with 5% as large a surface area, located in a low-SAV soil.
Carbon steel (above-ground, coated)	Delays onset of corrosion by N(9,3). Then it corrodes like a low-SAV, underground tank with a failed coating, and 5% as large a surface area.

Carbon steel (underground, impressed current cathodic protection)	PACE baseline after mN(10,5) years
Carbon steel (underground, impressed current cathodic protection, coated)	Delays onset of corrosion by max [mN(10,5), N(7,3)]. Then it corrodes like a similar coated tank whose coating has failed.
Stainless steel	Corrosion rate of 25% of that applicable to steel.
Fiberglass	No corrosion
Concrete	Gradually disintegrates due to chemical attack, but this effect has been included with ruptures.

- Sources and Explanations:

Carbon steel (underground, unprotected): PACE

Carbon steel (underground, coated): Corrosion will not begin until the coating has failed. The coating is assumed to fail according to a normal distribution, N(7,3). The 7-year mean was obtained from A.H. Roebuck and G.H. Brevoort, "Coating Work Costs and Estimating," Materials Performance, 22(1): 43-47 (Jan. 1983). Standard deviations were estimated by doubling the reported variations between average coating lives in differing environments. In addition, the standard deviation was increased 50% to account for variations in sub-grade drainage and the possibility of scratches during installation. The coating used was 2-coat coal-tar epoxy with an SP10 (near white blast) surface preparation. The mean age to failure is that reported for coatings in a freshwater environment.

Once the coating has failed, there is a near certainty of localized corrosion at the points of failure, for those points present excellent point anodes. The time-to-failure distribution must therefore be adjusted to reflect the certainty of a point anode's existence. We do this by dividing each probability in the PACE baseline distributions by the corresponding year-30 failure probabilities. The following time-to-failure distributions therefore apply following coating failures:

Tank Age	Low SAV(%)	Medium SAV(%)	High SAV(%)
4	0	0	0
9	0	14.5	32.0
14	9.0	38.0	59.9
19	34.3	70.9	91.8
24	69.1	87.9	95.9
30	100.0	100.0	100.0

Carbon steel (aboveground, uncoated). We assume that above-ground tanks only experience localized corrosion at their seams and their points of contact with cradles. These areas account for approximately 5% of their surfaces. We assume that air is about as corrosive as a low-SAV soil. Thus, these tanks corrode like low-SAV, underground tanks of 5% as large a surface area. The effect of area on corrosion rates is discussed below under "variations."

Carbon steel (aboveground, coated). The coating lifetime was based on Roebuck and Brevoort's values for exterior coatings in a moderate atmosphere. The result is a coating lifetime at N(9,3). Once the coating has failed, the tanks will have a 100% chance of developing point anodes (at the sites of initial coating failure), and will corrode like underground, coated tanks of 5% the surface area, in a low-SAV environment.

Carbon steel (underground, impressed current cathodic protection). We chose impressed current as the preferred means of cathodic protection on the recommendation of the National Association of Corrosion Engineers (NACE) (Houston, phone conversation). This recommendation was given because such a system can be repaired without excavation. Furthermore, a crude check of its functioning can be done merely by observing the ammeter.

The components of such a system are crucial. The wiring is not subject to protection, so it is failure-prone. The rectifier is also subject to failure, especially if much energy is dissipated. In addition, cathodic protection can fail if the local electrical environment changes (e.g. interference with another protected system across the street, or if someone buries some unprotected metal nearby).

Impressed-current cathodic protection therefore requires an inexpensive check of current distribution every 2-3 months (6 months maximum). This can be done by a contractor equipped with a hand-held meter, and takes only 2-3 minutes (plus travel).

With regular maintenance, NACE says such a cathodic protection system should last for a long time. No failure data appears to be available, however, and NACE says failures are common among poorly-maintained systems. We therefore assume that cathodic protection systems fail with a distribution of (m)N(10,5), where m is a random number drawn from (1, 3) indicating the stochastic quality of the maintenance effort. (1 means no maintenance). Source: BEJ following phone conversations with NACE.

As long as cathodic protection is functioning, corrosion will be negligible.

If cathodic protection fails and is repaired after a substantial interval, it may be too late to restore complete protection. Cathodic protection does not function well for creviced surfaces (or pits), for it is difficult to get an adequate charge density. (Source: NACE/API, Corrosion of Oil-and Gas-Well Equipment (1958), p. 71.) Since belated repair will be insufficient to halt established localized corrosion, we have not modeled belated repairs of the cathodic protection system. Ordinary maintenance, however, is already included in our time-to-failure distriution.

Carbon steel (underground, impressed current cathodic protection, coated). If cathodic protection and a coating are both used, both the cathodic protection system and the coating must fail before corrosion will occur. Once failure occurs, point anodes will exist at the points of coating failure.

Stainless steel. Stainless steel corrodes four times more slowly than unprotected carbon steel. Source: Peters & Timmerhaus, Plant Design and Economics for Chemical Engineers, 3rd. Ed., (1980), p. 574.

Concrete. The disintegration of concrete leads to cracking, not to localized corrosion holes. We will discuss the cracking of concrete tanks under ruptures, event T1124, below.

VOLUME OF RELEASE:

- Tank corrosion represents a growing leak. Eventually the leak rate will reach a detectable level.

ASSUMPTIONS:

- Corrosion holes start small. Assume initial hole size follows a beta distribution, with a minimum size of (1/64)", a maximum of (1/4)", and a mode of (1/32)".

- Corrosion holes grow with time. We use the corrosion rate, r, calculated earlier, as the base rate at which corrosion holes grow in radius. In addition, once exterior corrosion holes have perforated the tank, they will also grow because of generalized interior corrosion (see event T1125). We therefore add this corrosion rate to r in order to determine the total rate at which the hole grows in radius.

- Corrosion holes may occur anywhere on the tank. Depending on such factors as water table depth, they may be more likely to occur on the bottom of the tank. We have decided to assume that the average corrosion hole occurs on the tank bottom. This estimate could be refined to account for fluctuations in fluid levels and the fact that leak rates are not linearly dependent on hydraulic head. Such refinements greatly complicate the model, however, without significantly altering the leak rates. Hence, we use simple "average" hydraulic heads throughout the model, rather than integrating loss rates over the cyclical fluctuations in fluid depths.

- For storage tanks, we assume that the average fluid depth is 50% of the tank height. For treatment tanks we assume that the average fluid depth is 80% of the tank height.

- For underground tanks, the leak rate is calculated according to the underground leak rate formula. (Section A.1.1). For above-ground tanks or tanks in vaults, the Bernoulli equation (Section A.1.2) applies.

VARIATIONS:

- Tank capacity. Localized external corrosion is an electrochemical process which will only occur if the tank surface experiences a non-uniformity which can function as a locale for electrochemical attack. Such non-uniformities are referred to as "point anodes" and may consist of scratches in the tank wall, variations in local soil conditions, or stones or cinders in contact with the tank wall.

  Logically the probability that point anodes will be present is a function of tank surface area: the larger the tank, the higher the probability that a point anode exists. Similarly, the larger the tank surface area, the more likely it is that there is an unusually active point anode somewhere on the tank surface.

  The easiest way to account for this factor is to adjust the corrosion rate r to account for the surface area of the tank. According to a pipe corrosion model by Rossum (see event B13 for a full discussion), the corrosion rate for the deepest pit is proportional to the .16 power of the surface area. Therefore, variations in tank size can be accounted for by adjusting r according to the following formula:

  $$r = r_0 \, (A/A_0)^{.16}$$

  where

  r = the adjusted corrosion rate
  r_0 = the corrosion rate obtained from the PACE data
  A = the surface area of the tank under consideration and
  A_0 = the average area of the tanks included in the PACE study

  These tanks were all service station tanks, many of which were installed prior to 1970; they probably averaged 5000 gallons in capacity. The surface area of such tanks is approximately 440 square feet.

  This area adjustment factor applies to coated tanks and stainless steel tanks as well as to carbon steel tanks, for in all cases, an increase in tank surface area increases the probability that there is an unusually active pit.

- Stray currents can accelerate corrosion. Approximately 10% of tanks are subjected to stray currents due to nearby electrical equipment or electrical rail lines. (Source: Warren Rogers, Warren Rogers Associates, personal communication.) Stray currents approximately double external corrosion rates. (Source: Warren Rogers, Warren Rogers Associates, personal communication.) In order to allow greater variability in this effect, we have assumed that stray currents multiply the corrosion rate r by a stochastic factor of x. x is distributed according to a beta distribution with a minimum of 1, a mode of 2, and a maximum of 4.

- If the leak is detected, the tank will be repaired or replaced, and the aging process will start over again, using the same parameters as those used for the original tank.
- Cathodic protection will have no effect on hole growth rates; once the cathodic-protection system has failed, the tank will corrode in the same ma as an unprotected tank.
- Coatings will also have no effect on hole growth rates.
- Double-walled tanks: The 2 walls of such tanks are modeled separately. Exterior corrosion attacks the outside of the outside wall. Interior corrosion attacks the inside of the inside wall. The interstitial space is not subject to corrosive attack. The interstitial alarm is modeled as a leak detector similar to that used in a vault. See event MOALARM, below.
- In-ground tanks or above-ground tanks on-grade. Both the above- and below-ground sections of such tanks are subject to corrosion. Because exterior corrosion is more rapid below-ground than above-ground, however, we have only modeled exterior corrosion of the below-ground segment. Similarly, since interior corrosion is most important on the bottom of the tank, we have only modeled interior corrosion of the tank bottom.

USER INPUTS:

- Tank surface area
- Corrosion protection methods employed
- Tank material
- Soil characteristics
- Rate of generalized interior corrosion (from event T1125)
- Tank wall thickness
- Tank location (above-, below-, or in-ground)
- Is the tank double-walled?

LABEL: T1123

FAILURE: Localized interior corrosion

SOURCES:

- API Tank and Pipe Leak Survey (referenced in SCS Engineers, "Assessment of the Technical, Environmental, and Safety Aspects of Storage of Hazardous Waste in Underground Tanks," Draft, 1983).
- PACE corrosion study, cited under event T1121.
- Best engineering judgment.

ASSUMPTIONS:

- Interior corrosion leaks are the same size and grow at the same rate as exterior corrosion holes.
- Volumes are larger, however, for the hole usually occurs at the bottom of the tank and therefore has more hydraulic head than that assumed for exterior corrosion holes.

CALCULATIONS:

- Using SCS Engineers' analysis of API survey data, we can construct the following tabulation of underground tank leaks:

Source of Leak	# of Failures	% of Total	Scaled to 77%
- TANKS			
localized exterior corrosion 776 + 212	988	61.6	77.0%
interior corrosion	194	12.1	15.0%
other	55	3.4	4.3%
loose fitting	9	0.6	0.8%
breakage	17	1.1	1.4%

- PIPES & ANCILLARY

pipe corrosion	353	22.0	27.5%
loose pipe fitting	64	4.0	5.0%
flex connector	38	2.4	3.0%
breakage	43	2.7	3.4%
other	54	3.4	4.3%
	1603		

- Explanation:

  - We obtained the last column by scaling the first entry to 77%. We then multiplied the remaining entries in this column by the same scaling factor. This scaling factor is based on Warren Rogers' assertion that 77% of all tanks exhibit significant localized exterior corrosion. This percentage is also consistent with the PACE data, which show that 76.6% of medium-SAV tanks have leaked by year 30. Due to the possibility that a tank system may experience more than one type of failure, the numbers in this column do not sum to 100%.

  - Line 1 includes 212 tanks that were not reported as failing by localized exterior corrosion. We included these tanks because we assumed that localized exterior corrosion is a slower process than the other four forms of tank failure. Thus, we assume that 77% of the 275 tanks that failed by these other mechanisms were undergoing undiscovered localized exterior corrosion at the time they failed. We make no similar adjustment to account for tanks that might have been undergoing localized exterior corrosion at the time of piping failures, because we assume that tank and piping systems are repaired independently. Thus, the API survey data already account for systems which suffer both tank and piping failures.

- We can read the following results off the above table:

Failure Mechanism	Probability	Conditional Distribution
exterior tank corrosion	0.77	See event T1121
interior tank corrosion	0.15	See below
seam leaks (the most likely form of "other")	0.043	See event T1124
tank rupture (breakage)	0.014	See event T1124
pipe corrosion	0.28	See event B13

pipe rupture (breakage)	0.034	See event B11
loose fittings	0.05	See event B121

PROBABILITY DISTRIBUTION: Conditional normal

PROBABILITY:

- .15c where c is a material-dependent coefficient given by the following table:

Tank material	c
steel	1
stainless steel	1
fiberglass	0
concrete	0

Coefficient c merely indicates that fiberglass does not corrode and that instead of treating the aging of concrete as corrosion, we will treat it as contributing to rupture under event T1124, below.

TIME-TO-FAILURE:

- We estimate that localized interior corrosion should occur more quickly than localized exterior corrosion. Since the PACE data show that the conditional mean date of localized exterior corrosion failure for tanks in medium-SAV soils is approximately 16 years, we assume that localized interior corrosion proceeds twice as fast. Thus, for quarter-inch steel, we have assigned a localized interior corrosion time-to-failure distribution of N(8,5). In choosing this distribution, we have used a relatively large standard deviation in order to cover unknown factors, including variations in yearly flow rates.

- Let x be the failure date sampled from N(8,5). Since the typical service station tank is .25" in thickness, the corrosion rate (r) for those tanks which experience localized interior corrosion is given by:

$$r = \frac{.25}{x}$$

In deriving this equation, we have assumed that localized interior corrosion was the primary corrosion mechanism for those tanks listed as failing by interior corrosion.

- We can now compute the failure date by using the combination of localized interior corrosion and generalized exterior corrosion to keep track of remaining wall-thickness. Because generalized exterior corrosion is usually much slower than localized interior corrosion it usually has only a minor effect on the date of failure. For this reason, we did not account for it in calculating our corrosion rate r, above. Generalized exterior corrosion is only important in those cases when it occurs unusually quickly.

VOLUME:

- Interior corrosion holes begin with the same size distribution as exterior corrosion holes, and grow in radius at the rate r calculated above.
- In addition, corrosion holes will also grow due to the effects of generalized exterior corrosion. See event T1126, below.
- Interior corrosion leaks tend to occur at the bottom of the tank. For storage tanks, we assume that the tank is on average 50% full; for treatment tanks, we assume that it is 80% full.
- For underground tanks, we calculated leak rates according to the underground leak rate equation (Section A.1.1). For above-ground tanks, tanks in vaults, or the above-ground sections of in-ground or on-grade tanks, the Bernoulli equation (Section A.1.2) applies.

VARIATIONS:

- Coated steel. We assume that the coating is 3-coat epoxy. Then the distribution of coating failure times is N(7,3). Source: Roebuck and Brevoort (1983). Corrosion will not begin until the coating fails. We assume that the failure of interior coatings does not influence either the probability of corrosion or the corrosion rate for interior corrosion. Thus tanks with failed interior coatings experience interior corrosion in the same manner as new, uncoated tanks.
- Cathodic protection. Cathodic protection has the same effects and the same time-to-failure distribution for interior corrosion as it has for exterior corrosion. We have assumed that when the exterior cathodic protection system fails, the interior cathodic protection system also fails.
- Double-walled tanks. See event T1121.
- Tank capacity. Unlike localized external corrosion, localized interior corrosion is not likely to be correlated with tank capacity. Localized internal corrosion is most likely to occur beneath the fill tube, and the affected area is likely to be influenced by factors such as method of filling or pumping rate, rather than tank size.
- Stainless steel tanks. Stainless steel tanks corrode at 25% of the rate applicable to carbon steel.

USER INPUTS:

- Rate of generalized exterior corrosion
- Tank material
- Tank wall thickness
- Type of corrosion protection system

LABEL: T1124

FAILURE: Tank Rupture

ASSUMPTIONS:

- Tank rupture can occur from inadequate component strength, settling, or exterior force.
- Tank rupture includes both large cracks and seam leaks.

SOURCES: See T1123 (Breakage + "other")

CALCULATIONS:

- SCS/API data (see event T1123) indicates a tank rupture rate of 1.4%.
- SCS/API data indicates a seam leak rate of 4.3%.
- SCS/API data indicates an average tank age of 10.8 years.
- Assuming ruptures are approximately uniformly distributed over the 10.8 years of tank lifetime, the average annual probability of ruptures is 5.7%/10.8 yrs = 5.3×10^{-3}/yr.

PROBABILITY: 5.3×10^{-3}/yr

PROBABILITY DISTRIBUTION: Binomial

VOLUME:

- Ruptures may take 2 forms: large cracks and seam leaks. The data from event 813 indicate that 75% of ruptures are seam leaks, while 25% are large cracks.
- Seam leaks are assumed to range in length from 0 to 5 ft, and in width from 0 to (1/16)".
- Large cracks are assumed to range in length from 3" to 36" and in width from 0 to 3".

VARIATIONS:

- Aboveground, in-ground, or vaulted tanks. Above-grade ruptures occur because of different types of accidents than occur for below-ground tanks. Vehicle collisions, collisions with fork-lifts, and inadequate component strength are major causes of ruptures. We assume that the probability of rupture is still 5.3×10^{-3}. Volume of loss will be limited by the amount of fluid in the tank.

- Fiberglass tanks. Fiberglass tanks are approximately twice as likely to rupture as steel. The probability of rupture is therefore 1×10^{-2}/yr. Source: Brown Minneapolis Tank Co., personal communication 4/30/85. Brown Tank Company said that 2% of fiberglass tanks collapse in the first couple of years. We obtained our scaling factor of 2 by comparing that percentage to the .5% annual probability of steel tank rupture.

- Double-walled tanks. We assume that since the inner wall of a double-walled tank is subject to fewer stresses than is the wall of a single-walled tank, it is only 50% as likely to rupture. The outer wall of such a tank, though, is likely to be just as vulnerable to rupture as the wall of a single-walled tank. We assume, however, that there is only a 50% chance that a rupture of the outer wall will also breach the inner wall. Since ruptures of the inner wall do not involve large exterior forces (such as vehicle collisions or settling of the backfill), we assume that the number of times that interior ruptures also breach the outer wall is small enough to be ignored.

  When a rupture of a double-walled tank occurs, infiltrating soil moisture or leaking hazardous waste will trigger the interstitial alarm. There is a 10% probability that the alarm will fail to function. See MOALARM, below.

LABEL: T1125

FAILURE: Thickness loss due to generalized interior corrosion.

ASSUMPTIONS:

- This event will cause a loss when remaining wall-thickness reaches zero.
- This event will also reduce the time it takes for localized exterior corrosion holes (if any) to penetrate the tank.

SOURCES: Perry and Chilton (1973).

CALCULATIONS:

- According to Perry and Chilton, generalized interior corrosion rates of .002"/yr to .02"/yr are reasonable. We expect that the lower corrosion rates are the most likely.

VOLUME: See event T1123.

PROBABILITY DISTRIBUTION: Uniform

PROBABILITY:

Cumulative Probability	Corrosion Rate
0.00 to 0.65	0.002"/yr
0.65 to 0.90	FNU(.002,.01)
0.90 to 1.00	FNU(.01,.02)

VARIATIONS:

- Coatings. See event T1123.
- Cathodic protection. See event T1123.

LABEL: T1127

FAILURE: Thickness loss due to generalized exterior corrosion.

ASSUMPTIONS:

- This event will reduce the time it takes for interior corrosion holes (if any) to penetrate the tank, as well as increasing the rate of interior hole growth once a hole occurs.

SOURCES:

- "Prediction of Leaks in Unprotected Storage Tanks," Warren Rogers Associates, Inc., included in correspondence package from Betsy Tam, EPA, to Chris Lough, PRA.
- W. H. Ailor, <u>Atmospheric Corrosion</u> (John Wiley and Sons: New York) 1982, p. 33.

CALCULATIONS:

- According to Ailor, generalized corrosion in an air environment occurs at approximately 1.4 mils/yr.
- According to Warren Rogers Associates, generalized corrosion is unlikely to cause failure (for a quarter-inch tank) within the 40-year time-horizon of their data.
- Generalized external corrosion in a soil environment is unlikely to occur more slowly than in air. 1.4 mils/yr is therefore a minimum value for the generalized external corrosion rate.
- 5 mils per year is a suitable upper bound for the generalized corrosion rate. This choice correspondes to a 50-year minimum time-to-failure for quarter-inch steel tanks in non-extreme environments.
- SAV will have some effect on generalized corrosion. Assuming the effect is roughly linear, and noting that according to the Canadian data the average SAV is 10, we account for SAV by a multiplying the generalized exterior corrosion rate by SAV/10. Under no circumstances, however, do we use a generalized corrosion rate of less than 1.4 mils/yr.

CORROSION RATE:

$$r_{gen,\ ext} = \max \left[.0014, \left(\frac{SAV}{10}\right) FNU\ (.0014,\ .005)\right]$$

where

$r_{gen,\ ext}$ = the generalized external corrosion rate.

VARIATIONS:

- Direct currents will have the same effect on generalized exterior corrosion as they have on localized exterior corrosion.
- Stainless steel tanks will corrode at one-fourth the rate applicable to steel tanks. See event T1121.
- Above-ground tanks. The atmospheric corrosion rate of 1.4 mils/yr applies (or one-fourth of that for stainless steel tanks).
- Cathodic protection or coatings. Significant generalized exterior corrosion will not begin until corrosion protection fails. Since generalized exterior corrosion is not influenced by the presence of point anodes, we assume that once the coating has failed, generalized exterior corrosion proceeds in the same manner for coated and uncoated tanks.

LABEL: T1128

FAILURE: Tank fails due to generalized corrosion.

ASSUMPTIONS:

- Tank corrosion may occur generally, due to a combination of rapid generalized exterior and generalized interior corrosion.

CALCULATION:

- Tank wall-thickness must be computed even for tanks without localized corrosion. In a few cases, this will produce corrosion failure.

VOLUME:

- We determine the sizes and the growth rates for these holes in the same manner as we determine the sizes and growth rates for localized corrosion holes.

LABEL: B11

FAILURE: Pipe Rupture

SOURCES: SCS Engineers' analysis of API data (see event T1123).

CALCULATIONS:

- According to the API data, 3.4% of service station tanks experienced pipe rupture. (See the table entry labeled "breakage" in event T1123).
- These tanks had been in use an average of 10.8 years.
- The annual rupture probability is therefore 3.4%/10.8 = 3.15×10^{-3}/yr.

PROBABILITY DISTRIBUTION: Binomial

PROBABILITY: 3.2×10^{-3}/yr

VOLUME:

- We assume minimum and maximum crack sizes of 1" x .1" and 10" x (1/4)", respectively.
- We assume that rupture dimensions are uniformly distributed over the range of possible values. Therefore:

  width = FNU(.1,.25) inches
  length = FNU(1,10) inches

- We determine hydraulic heads by applying the pipe-pressure formula (Section A.1.5) to the geometry of the system design under consideration. We assume that the rupture occurs at the midpoint of the pipe.
- Loss will only occur during filling or discharging. We calculate fill/discharge duration according to Section A.1.6.

VARIATIONS:

- Pipe length and system geometry will vary with system design.
- Above-ground pipes or pipes in vaults. We assume that the rupture probability for above-ground pipes is the same as that for underground pipes. We also assume that the hole size distributions are the same for both types of pipes.
- Fiberglass pipes. The probability of rupture is doubled. See event T1124.
- Multiple pipes. We evaluate each pipe separately. We assume that the rupture of one pipe has no influence on the probability that other pipes will also rupture.

USER INPUTS:

- System geometry
- Pipe diameter
- Pipe length

LABEL: B121

FAILURE: Welded Flange Leak

SOURCES:

- Nuclear Regulatory Commission, Reactor Safety Study (1975).
- Henley and Kumamota (1981).
- SCS Engineers (1984).

ASSUMPTIONS:

- A flange leak can only occur when fluid is in contact with the flange. If the flange is located at the top of the tank, fluid only contacts it during filling, discharging, or overflow. If the flange is at the bottom of the tank, fluid will always be in contact with it. The location of the flange is dependent on system design.

CALCULATIONS:

- 3×10^{-7}/hr = welded flange leak rate (Reactor Safety Study).
  3×10^{-7}/hr = .003/yr
- 10^{-4} to 10^{-1} per 10,000 hrs = welded flange leak rate (Henley & Kumamoto).
  10^{-4} to 10^{-1} per 10,000 hrs = 8.8×10^{-5} to 8.8×10^{-2}/yr. The geometric mean of this range of values = .0028/yr.
- API service station data gives a loose fitting rate of 5.0% (SCS Engineers). The average system age is 10.8 yrs. The failure rate is therefore 5.0%/10.8 = 4.6×10^{-3}/yr.
- We therefore use a conservative flange leak probability of 5×10^{-3}/yr.

PROBABILITY DISTRIBUTION: Binomial

PROBABILITY: 5×10^{-3}/yr

VOLUME:

- The flange is at the point of attachment of the pipe to the tank.
- The pressure drop due to friction losses therefore includes the entire length of the pipe.
- The elevation change can be calculated from the system geometry.
- We assume a 50% weld failure as upper bound, 0 as lower bound. I.e., we assume that the length of the breach is distributed according to FNU(0, 50% of flange circumference). We assume that the width of the breach is given by FNU(0,1/8) inches.
- We assume a 300 to 400 lb flange. The exterior flange diameter is 6.5". (Source: Perry and Chilton, Chemical Engineers' Handbook, 5th Ed. (1973), pp. 6-66 and 6-67, using a 2"-diameter pipe). The maximum weld failure is therefore 10" long.
- For underground flanges, we calculate the leak rate by using these values in the underground leak rate formula (Section A.1.1). For above-ground flanges (or flanges in an air environment such as a vault) we use the Bernoulli equation (Section A.1.2).
- We calculate the loss per day by multiplying the leak rate by the length of time that the fluid is in contact with the flange.

VARIATIONS:

- Flange location. A flange may be at the top of the tank or near the bottom of the tank. Its location will influence the hydraulic head of the fluid and will determine the fraction of the time that the flange is in contact with fluid. The flange location will be determined by the choice of system design.
- Multiple flanges. We evaluate each flange independently. Thus, we assume that the failure of one flange has no influence on the probability that other flanges will leak.

USER INPUTS:

- System design

LABEL: B122

FAILURE: Gasket Fails

ASSUMPTIONS:

- We model gasket deterioration as an erosion-like process. We assume that under ideal conditions, it will occur relatively slowly, at a rate of less than 50 mils per year.

SOURCE:

- Best engineering judgment based on Nuclear Regulatory Commission, Reactor Safety Study (1975), and EPA, Case Studies 1-23 (1984) (case study #4).

PROBABILITY DISTRIBUTION: Empirical

PROBABILITIES (baseline):

Cumulative Probability	Deterioration Rate (mils/yr)
0.00 to 0.77	FNU(0,12.5)
0.77 to 0.83	FNU(12.5,25)
0.83 to 1.00	FNU(25,50)

DATE OF FAILURE:

- For a 2" pipe, the standard gasket is a flat disk with an inner radius of 1" and an outer radius of 2.0625". Since disintegration occurs from the inside outward, 1.0625" of gasket must be dissolved or eroded before the fluid can escape. A gasket for a 4" pipe is slightly thicker (1.4375"). (Source: Perry and Chilton, 1973).

VOLUME: See event B121 (welded flange leaks).

COMMENTS:

- Under ideal conditions, we have assumed that a gasket will deteriorate very slowly. Waste/gasket interactions will speed up the deterioration process, however. To model such interactions we use a multiplicative factor selected from FNU(1,20). Gasket failure can therefore occur as early as year 2. This is consistent with the facts of EPA case study number 4 (Biocraft site).

- The Reactor Safety Study quotes a failure rate for containment-quality gaskets of 3×10^{-6}/hr = 2.6%/yr. This may be too low for a conventional hazardous waste tank system, but it serves as an approximate check for the results of our gasket disintegration model.

LABEL: B13

FAILURE: Pipe Corrosion

SOURCES:

- John R. Rossum, "Prediction of Pitting Rates in Ferrous Metals from Soil Parameters, Jour. AWWA, 1969, pp. 305-310.
- PACE (see event T1121).
- SCS Engineers analysis of API survey data (See event T1123).

PROBABILITY DISTRIBUTION: Cumulative Empirical

CALCULATIONS (underground pipes):

- Localized exterior corrosion

  Rossum gives the following formula for maximum exterior pit depth for buried steel pipes:

$$p = 1.06K_n\left[\frac{(10-pH)t}{\rho}\right]^n A^{.16}$$

where

p = the depth of the deepest pit (in mils)

K_n = 170 for soils of good aeration
= 222 for soils of fair aeration
= 355 for soils of poor aeration

pH = the soil pH (must be between 5 and 9)

n = 1/6 for soils of good aeration
= 1/3 for soils of fair aeration
= 1/2 for soils of poor aeration

= the soil resistivity (ohm-cm)

t = the number of years since the pipe was buried

A = the surface area of the pipe (in square feet)

We have added a fourth aeration category, moderate aeration. We obtained K_n for this category by averaging the values for good aeration and fair aeration. We obtained the value of n by taking the geometric mean of the values for good and fair aeration. Thus:

K_n = 196 for soils of moderate aeration

n = .236 for soils of moderate aeration

- Multiple failures. Unlike our tank-corrosion model, which only predicts the date of first failure, the Rossum pipe-corrosion model can be used to determine the occurrence of subsequent corrosion holes. The number of leaks (L) at time t is given by:

$$L = A\left[\frac{1.06K_n}{z}\right]^{6.25} \cdot \left[\frac{t(10-pH)}{\rho}\right]^{n/.16}$$

We make this formula stochastic by converting fractional values of L into probabilities. Thus, we have assumed that the first leak occurs between L = 0 and L = 2. At L = 1, there is a 50% chance of failure. Similarly, the second leak occurs between the times when L = 1 and L = 3, the third leak between L = 2 and L = 4, etc. This means, for example, that a value of L equal to 3.2 means that 2 leaks have occurred with certainty; there is a 60% chance that a 3rd leak has occurred, and if the third leak has occurred, there is a 10% chance that the 4th leak has also begun.

Note that the value of t is set to zero whenever detection/repair occurs.

Caveat: The Rossum model applies only for soil pH between 5 and 9. Outside that range, other corrosion mechanisms come into play. These are not included in our model.

- Generalized interior corrosion. When fluid is in contact with the pipe, we assume that generalized interior corrosion occurs under the same probability distribution as applies to tanks. Because these are independent events, however, we determine the corrosion rates separately for each tank and each pipe. When the pipe is in contact with air, we use a corrosion rate of 1.4 mils per year (Ailor, 1982). When we combine corrosion from the fluid and corrosion from the air, we obtain a generalized interior corrosion of:

$$1.4(1-f) + f(r')$$

where

f = the fraction of time the pipe is in contact with the fluid

r' = the corrosion rate obtained for those times when fluid is present

Caveat: The Rossum model applies only for soil pH between 5 and 9. Outside that range, other corrosion mechanisms come into play. These are not included in our model.

- Localized interior corrosion. Since our tank-corrosion model shows that localized interior corrosion is 19% as likely as localized exterior corrosion, we assume that the same ratio applies to pipes. We cannot use this information directly, however, because our localized exterior pipe-corrosion model only applies if soil conditions are known. We therefore must use API service station data to determine the probability that pipes undergo localized interior corrosion. From this, we can then obtain the probability of localized interior pipe corrosion.

  According to the API data, 28% of service station tanks experience pipe corrosion. Since service station tanks generally have two pipes, we convert this value to a per-pipe probability by assuming that corrosion is equally likely in either set of piping. Thus, letting "a" be the probability of localized corrosion for a single pipe, it must be the case that:

  $$.28 = 1 - (1-a)^2$$

  or, a = .15. Thus, if localized interior pipe corrosion is 19% as common as localized exterior pipe corrosion, and if other forms of corrosion failure are uncommon, then approximately 2.4% of the API survey pipes failed by localized interior corrosion, while 12.6% failed by localized exterior corrosion.

  We assume that the time-to-failure distribution for localized interior corrosion is the same for pipes and tanks. Thus, the time-to-failure distribution for those pipes which exhibit localized interior corrosion is N(8,5).

  We adjust for area by multiplying both the probability of localized corrosion and the corrosion rate by $(A/10)^{.16}$. See the discussion of above-ground pipes, below, for an explanation of this area correction factor.

- Generalized exterior corrosion. Generalized exterior corrosion reduces the time to pipe failure by localized interior corrosion in the same way that it reduces the time to interior corrosion failure for tanks. We assume that generalized exterior corrosion rates for pipes follow the same probability distribution as applies to tanks. See event T1127.

- Erosion. Because pipes carry moving fluids, they are subject to erosion by suspended solids in the waste. Erosion rates are dependent on the concentration of suspended solids. Since our baseline corrosion values are derived for pipes carrying a non-erosive fluid (gasoline), we assume that they do not already account for erosion. We therefore add the following erosion rates to both our localized interior and generalized interior corrosion rates:

Fraction of suspended solids in the waste (ppm)	Erosion rate (mils/yr)
<1,000	0
1,000-10,000	FNU(0,5)
>10,000	FNU(5,10)

VOLUME OF RELEASE:

- We assume that localized exterior corrosion holes follow the same size distribution for pipes as they do for tanks. We calculate their growth rates in the same manner as we calculate growth rates for exterior corrosion holes in tanks.

- Localized interior corrosion holes also follow the same size distribution and grow in the same manner as do the corresponding holes in tanks.

- If the pipe fails due to generalized corrosion, the holes will be larger than they will be for localized corrosion. We assume that such holes begin with the dimensions of a pipe rupture (see event B11), and double in length and width each year until they are detected. In order to account for the physical limitations imposed by the dimensions of the pipe, we do not allow such corrosion holes to become more than 3" wide or longer than the length of the pipe.

- We calculate fluid velocity, transfer time, and pressure in the same manner as we used for underground pipe ruptures. For both corrosion holes and ruptures, we make the simplifying assumption that the leak occurs at the midpoint of the pipe.

- We use the underground leak rate equation (Section A.1.1) to calculate loss rates. Multiplying this leak rate by the fill or discharge time (Section A.1.6) then gives the total volume of loss per filling or discharging.

ABOVE-GROUND PIPES:

- The Rossum Model does not apply to above-ground pipes.

- Localized exterior corrosion. We obtain the localized exterior corrosion rate for above-ground pipes from the following conditional normal distribution:

$$.11 \left(\frac{.05A}{10}\right)^{.16} \left[N(16(10/.05A)^{16}, 6.6(10/.05A)^{.16}\right]$$

where

A = the surface area of the pipe in square feet.

- Interpretation. The first term of this formula, $.11(.05A/10)^{.16}$ is the probability that localized exterior corrosion occurs. The $(A/10)^{.16}$ factor is the same area adjustment factor that we use for tanks, except that for pipes, the baseline area is 10 square feet. This area corresponds to 20 feet of 2" pipe or 10 feet of 4" pipe. These pipe dimensions are appropriate for service station fill and discharge pipes, respectively.

  The .11 coefficient in this expression is the baseline probability of localized exterior corrosion. We derived this probability from a combination of the PACE tank data and the API pipe-corrosion data. According to the PACE data, 70% of low-SAV tanks fail by localized exterior corrosion within 30 years, while 77% of medium-SAV tanks fail by that mechanism in the same period. According to the API data, 12.6% of service station pipes fail by localized exterior corrosion. If we assume that this percentage applies to medium-SAV soils and that the same proportionality factor applies to low- and medium-SAV pipes as applies to low- and medium-SAV tanks, then (70/77) x 12.6% of low-SAV service station pipes fail by localized exterior corrosion. To two significant figures, this percentage is 11%. If we assume that above-ground pipes corrode like low-SAV underground pipes (an assumption similar to that which we made for above-ground tanks) then we can apply this percentage to above-ground pipes.

  The second part of our localized exterior pipe-corrosion formula, $N(16(10/A)^{.16}, 6.6(10/A)^{.16})$, gives the conditional date of failure for pipes that experience localized interior corrosion. The factor $(10/A)^{.16}$ reduces the time to failure according to the inverse of the area adjustment factor. Thus, when a corrosion rate is calculated from the sampled time-to-failure, that corrosion rate will be higher than baseline by a factor of $(A/10)^{.16}$.

  Our baseline time-to-failure distribution in this expression is N(16,6.6). We derived this distribution in the same manner as we derived the 11% baseline probability of failure. According to the API survey data, service station pipes show the following distribution of failure dates:

Year of failue	Percentage of reported pipe failures
0-1	2.1
2-5	6.4
6-10	32.8
11-15	33.1
16-20	18.1
21-25	5.0
26-30	2.3
30+	0.2

We can approximate this distribution as N(12,5). Assuming that this distribution applies to medium-SAV pipes, we can obtain a low-SAV time-to-failure distribution by comparing the PACE distributions for medium- and low-SAV tanks. These distributions show conditional mean dates of failure of 21 and 16 years, respectively. Adjusting both parameters of the API distribution by 21/16 gives us a low-SAV time-to-failure distribution of N(16,6.6).

The final element of our above-ground localized corrosion formula is the .05 factor used to reduce the effective surface area of the pipe. We use this factor because we assume that like above-ground tanks, above-ground pipes are only vulnerable to localized exterior corrosion at their seams and points of support. These regions account for approximately 5% of their surface areas.

In our pipe-corrosion distribution, we have applied the area adjustment factor to both the baseline probability and the baseline corrosion rate. This is different from the way that we adjust for area in our tank corrosion model, for in that model, we only applied our area adjustment factor to corrosion rates.

We have modeled pipes and tanks differently because we believe that three factors control the onset of localized corrosion. One of these is the surface area of the buried metal. The others are the corrosivity of the soil and the care with which the component is installed. We have assumed that surface area is an important factor for localized corrosion events with low probabilities. In other words, we have assumed that the probability of pipe corrosion is relatively low because a pipe is small enough that it is relatively unlikely to experience a point anode. For tanks, however, the baseline probabilities of localized corrosion are on the order of 70-85%. We assume therefore, that the principal factors influencing the onset of tank corrosion are the corrosivity of the soil and the care with which the tank is installed. Surface area will be important, but its primary effect will be to determine the number of point anodes and thus the depth of the deepest pit.

We have generalized the preceding discussion to obtain the following rule of thumb: whenever the baseline probability of a corrosion event is less than 50%, we have assumed that component surface area will influence the probability of the onset of corrosion; whenever the baseline corrosion probability is over 50%, we assume that the component is already large enough that surface area has little influence on probability. Since all of our relevant baseline probabilites are either greater than 70% or less than 12%, we never had to elaborate this rule of thumb by developing a model to deal with intermediate cases. In addition, since our area adjustment factor requires an area more than 5000 times larger than baseline to increase a 12% probability to 50%, we did not need to modify that factor to assure that our area adjustments do not increase the probability of failure to a value greater than 50%. Finally, our model is insensitive to any choice of cut-off probabilities between 25% and 70%, so it is unnecessary for us to be precise in our determination of what value in that range is the theoretically best choice.

- Generalized exterior corrosion. Generalized exterior corrosion for above-ground pipe segments occurs at the atmospheric corrosion rate of 1.4 mils/yr.

- Localized interior corrosion and generalized interior corrosion. The corrosion rates for these types of corrosion are the same for above- and below-ground pipes.

- Combinations of corrosion mechanisms. We take combinations of corrosion mechanisms into account in the same manner for pipes as we used for tanks. Thus, to determine the date of interior corrosion failure, we compute the remaining wall-thickness for the combination of localized interior corrosion and generalized exterior corrosion. To determine the date of exterior corrosion failure, we calculate the remaining wall-thickness from the combination of localized exterior corrosion and generalized interior corrosion. To determine the date of generalized interior corrosion, we calculate the remaining wall-thickness from the combination of the two generalized corrosion mechanisms. We do not combine generalized exterior and localized exterior corrosion (or generalized interior and localized interior) because we assume that our localized exterior corrosion rates already include both forms of exterior corrosion.

- Pipe thickness. Pipe thickness is directly included as a parameter in the Rossum localized exterior corrosion model. For our PACE- and API-derived corrosion rate formulas, we use a baseline pipe thickness of 190 mils, which is the average of the thicknesses generally used for 2" and 4" pipe (Peters and Timmerhaus (1980)).

- Hole sizes. We use the same hole-size distribution for above- and below-ground pipes. We calculate hole growth rates in the same manner for both types of pipes.

VARIATIONS (above- and below-ground):

- Coated pipes. When a coating fails, there is a 100% chance of point anodes developing at the sites of coating failure. Thus, once the coating fails, localized exterior corrosion begins with certainty. Because the Rossum model does not take this factor into account, we use the following baseline time-to-failure distributions for low-, medium-, and high-SAV pipes:

Soil type	Piping time-to-failure distribution following coating failure
Low SAV	N(16,6.6)
Medium SAV	N(12,5)
High SAV	N(9,4)

These distributions are derived from the PACE and API data sets. The derivation process for high-SAV pipes is the same as that described earlier for medium- and low-SAV pipes.

These distributions apply to 190-mil pipes. We model different pipe thicknesses using the same approach that we used to model variations in tank wall-thicknesses.

- Cathodic protection. We assumed that the entire tank facility uses a cathodic protection system powered by a single power supply. Thus, when that system fails and repairs are not undertaken within a reasonable time, cathodic protection fails for both the tank and the pipes. Cathodic protection failure is discussed under events T1121. As long as it is functioning, cathodic protection will prevent both interior and exterior corrosion.

- Loss rates from above-ground pipes or below-ground pipes with secondary containment. Leak rates in such circumstances will be controlled by the Bernoulli equation (see Section A.1.2).

- Stray currents. If stray currents exist, they will affect pipes and tanks similarly. See event T1121. Because stray currents are likely to be equally severe for all elements of a tank system, we only sample the stray current event once for the entire facility.

- Stainless steel. Stainless steel reduces all corrosion rates by a factor of .25.

- Fiberglass. Fiberglass pipes do not corrode.

USER INPUTS:

- Pipe material
- System design
- Corrosion protection system
- Pipe thickness
- Surface area of pipe
- Soil characteristics

LABEL: A11111

FAILURE: Strainer drain left open after maintenance (or during pump-out for storage or accumulation tanks).

ASSUMPTIONS:

- We assume that the minimum operator response time is 15 seconds.
- Because the operator is likely to be in the vicinity, we assume a maximum response time of 3 minutes. We therefore assume that the response time is distributed FNU(.25,3) minutes.
- Strainer maintenance occurs once per month.

SOURCES:

- JRB Associates (1982)
- Nuclear Regulatory Commission, Reactor Safety Study (1975)

CALCULATIONS:

- 1.7×10^{-3} per operation = operator failure rate for operations embedded in a procedure (JRB).
- This is a relatively infrequent procedure (once per month) with no immediate feedback. Therefore, 1×10^{-2} (general failure rate for operations with no status display) is probably a better figure (Reactor Safety Study).

PROBABILITY DISTRIBUTION: Binomial

PROBABILITY: 1×10^{-2}/month

VOLUME:

- We assume that the leak rate is equal to the pumping rate.

VARIATIONS:

- Storage and accumulation tanks. For many of these tanks, the strainer will be included as part of the pump-out truck. In such cases, error in strainer maintenance will be detected and corrected at the first pump-out following pump maintenance.

- We assume that the pump-out truck visits 40 tanks per month.
- Let n be the number of pump-outs per month for the modeled tank (n may be less than 1). Then the probability is n/40 that the facility is the first one to be visited after any given strainer maintenance. The annual probability of a spill due to faulty maintenance of the pump-out truck's strainer is therefore given by:

$$1 \times 10^{-2} \times (n/40) \text{ per month} = 3n \times 10^{-3}/\text{yr}.$$

USER INPUTS:

- Number of pump-outs per month (n)

LABEL: A11112

FAILURE: Pump drain left open during pumping.

ASSUMPTIONS:

- This can only happen following pump maintenance.
- Pump maintenance occurs annually.
- The response time in the event of a spill is FNU(.25,3) minutes.

SOURCES:

- Nuclear Regulatory Commission, Reactor Safety Study (1975)
- JRB Associates (1982)
- Event A11111 (strainer drain left open)

CALCULATIONS:

- See event A11111

PROBABILITY DISTRIBUTION: Binomial

PROBABILITY: 10^{-2}/yr

VOLUME:

- The spill rate is equal to the pumping rate.

VARIATIONS:

- Storage and accumulation tanks. For many of these tanks, the pump-out pump is included as part of the truck. An error in pump maintenance will therefore be detected and corrected at the first pump-out following pump maintenance.
- We assume that the truck visits 40 sites/month.

- Let n be the number of pump-outs per month at the facility being modeled. Then the probability that the facility being modeled is the first one to be visited after pump maintenance is n/40, and the probability that it is the first one visited after faulty pump maintenance is given by:

$$(1 \times 10^{-2})(n/40) \text{ per year} = 2.5n \times 10^{-4}/\text{yr}$$

USER INPUTS:

- Number of truck visits per month (n)

LABEL: A1112

FAILURE: Hose ruptures (above ground) during pump-out (storage or accumulation tanks only).

ASSUMPTIONS:

- Hose ruptures inside the pump-out pipe will be inconsequential. Leakage will return to the tank in all but extraordinary circumstances.

SOURCES:

- JRB Associates (1982)

CALCULATIONS:

- Hose rupture probability = 1×10^{-4}/hr (JRB)
- Annual probability of hose rupture = 1×10^{-4}/hr x T hr/pump-out x n pump-outs/week x 52 weeks/yr = $5(nT) \times 10^{-3}$/yr

PROBABILITY DISTRIBUTION: Binomial

PROBABILITY: $5(nT) \times 10^{-3}$/yr

VOLUME:

- The maximum leak rate will be the pumping rate for the pump-out pump. The minimum is approximately 0.
- We assume that the leak rate is uniformly distributed between these two exremes.
- The maximum detection/response time is the entire discharge time (see Section A.1.6). The minimum detection/response time is about 15 seconds.

USER INPUTS:

- Number of discharges per week (n)
- Time required for pump-out (from Section A.1.6)

LABEL: A1113, A1114

FAILURE: Pump or strainer ruptures during pump-out (storage or accumulation tanks only).

SOURCES:

- U.S. Coast Guard (1978)
- JRB Associates (1982)

CALCULATIONS

- 1×10^{-8}/hr = strainer rupture rate (JRB)
- 1×10^{-8}/hr = pump rupture rate (JRB)

COMMENTS:

- These are very low probability events producing spills which will probably be contained by an above-ground pad. These events are therefore not included in our model.

LABEL: A1115

FAILURE: Loose flexible hose connection during pump-out (storage or accumulation tanks only).

SOURCES:

- Nuclear Regulatory Commission, Reactor Safety Study (1975)

CALCULATIONS:

- 1×10^{-2}/demand = general rate of human error (Reactor Safety Study)
- 1×10^{-2}/demand = $m \times 10^{-2}$/month where m is the number of pump-outs per month (m will generally be less than 1).

PROBABILITY DISTRIBUTION: Binomial

PROBABILITY:

- 1×10^{-2}/demand = $m \times 10^{-2}$/month where m is the number of pump-outs per year.

VOLUME:

- Assume that the maximum loss rate is the hose flow rate. So leak rate is FNU(0, hose flow rate).

USER INPUTS:

- Number of pump-outs/year (m)
- Tank capacity (Q)

LABEL: A2113, A2114

FAILURE: Strainer or pump rupture during tank filling.

SOURCES:

- U.S. Coast Guard (1978)
- JRB Associates (1982)

CALCULATIONS:

- 1×10^{-8}/hr = strainer rupture rate
- 1×10^{-8}/hr = pump rupture rate

COMMENTS:

- These are very low probability events producing spills which will probably be contained by an above-ground pad. These events are therefore not included in the computer model.

LABEL: A2116

EVENT: Pump Corrodes

ASSUMPTIONS:

- Pump corrosion is composed of:
  - generalized interior corrosion
  - localized interior corrosion
  - generalized exterior corrosion
  - localized exterior corrosion
  - erosion

CALCULATIONS:

- Our pump-corrosion model is very similar to our pipe-corrosion model.
- Localized interior corrosion. We model localized interior corrosion in the same way for pumps and pipes. Because a pump's complex shape makes it more vulnerable to localized interior corrosion than is a pipe, we use the same probability distributions for localized interior corrosion of pumps and pipes. See event B13, above.
- Generalized interior corrosion. Generalized interior corrosion is also the same for pumps and pipes.
- Generalized exterior corrosion. Because pumps are exposed to the atmosphere, we use a generalized exterior corrosion rate of 1.4 mils per year.
- Localized exterior corrosion. Because of the pump's small surface area and above-ground setting, localized exterior corrosion is highly unlikely and we have not included it in our pump-corrosion model.
- Erosion. Because of the pump's complex shape, it will be more subject to erosion than is a pipe. We assume the following dependence of erosion rate on fraction of suspended solids:

Fraction of Suspended Solids (ppm)	Erosion rate (mils per year)
0-10,000	FNU(0,10)
10,000	FNU(10,20)

VOLUME:

- We use the same hole sizes for pumps as we used for pipes.

COMMENTS:

- In some cases, pumps may be located inside the tank. In these cases, pump corrosion cannot produce a release of fluid.

LABEL: A210

FAILURE: Fluid flows over the top of an open-topped tank during overfill events.

ASSUMPTIONS:

- Open-topped tanks have a ready overflow route over the top of the tank.

VOLUME:

- The leak rate will be equal to the rate at which fluid is pumped into the system.
- The overflow may be detected and remedied immediately, or it may continue through the entire batch.
- We assume that the overflow duration is uniformly distributed between zero and the entire fill time for the tank. Thus, the overflow volume is given by FNU(0, volume of entire batch).

LABEL: A211

FAILURE: Fluid flows out the vent of an above-ground tank during overfill events.

ASSUMPTIONS:

- Above-ground tanks have a ready overflow route through their vents.

VOLUME:

- The leak rate will be equal to the rate at which fluid is pumped into the system.
- The overflow may be detected and remedied immediately, or it may continue through the entire batch.
- We assume that the overflow duration is uniformly distributed between zero and the entire fill time for the tank. Thus, the overflow volume is given by FNU(0, volume of entire batch).

LABEL: A213

EVENT: Pump-out pipe rupture leads to loss during overfill events.

SOURCES: B11

PROBABILITY DISTRIBUTION:

- Non-stochastic. This event will occur if the pump-out pipe has ruptured under event B11.

PROBABILITY: See event B11 (pipe rupture)

VOLUME:

- If there is a pump, we assume that it shuts off automatically. Then, the pressure at the point of the rupture will be determined by the static hydraulic head of the backed-up fluid.
- We assume that the average rupture occurs at the midpoint of the pump-out pipe. Then the hydraulic head can be determined from the system layout.
- We assume an overfill detection/response time of FNU(.25,60) minutes (the operator notices that the fluid is not flowing).

USER INPUTS:

- System design

COMMENTS:

- This event is only important for systems for which pump-out is by flexible hose. For these tanks, this event is the only source of loss through a ruptured pump-out pipe. For other tanks, losses by this mechanism will be overshadowed by losses through the same holes during normal discharge operations.

LABEL: A214

FAILURE: Pump-out pipe corrosion results in leak during overfill events.

SOURCES: B13

PROBABILITY DISTRIBUTION:

- Non-stochastic. This event will occur if the pump-out pipe has corroded under event B13.

PROBABILITY: See event B13 (pipe corrosion)

VOLUME:

- If there is a pump, we assume that it shuts off automatically. Then, the pressure at the corrosion hole will be determined by the static hydraulic head of the backed-up fluid.
- As in event B13, we assume that the average corrosion hole occurs at the midpoint of the pump-out pipe. Then the hydraulic head can be determined from the system layout.
- We assume an overfill detection/response time of FNU(.25,60) minutes (the operator notices that the fluid is not flowing).

USER INPUTS:

- System design

COMMENTS:

- This event is only important for systems for which pump-out is by flexible hose. For these tanks, this event is the only source of loss through a corroded pump-out pipe. For other tanks, losses by this mechanism will be overshadowed by losses through the same holes during normal discharge operations.

LABEL: A215

FAILURE: Outlet flange or gasket leak produces losses during overfill events.

SOURCES: See B121 or B122

PROBABILITY DISTRIBUTION:

- Non-stochastic. This event will occur if the flange or gasket is leaking under events B121 or B122.

PROBABILITY: See event B121 (flange leak) or B122 (gasket leak).

VOLUME:

- If there is a pump, we assume that it shuts off automatically. Then, the pressure at the point of the rupture will be determined by the static hydraulic head of the backed-up fluid. This will be determined by the system design.
- We assume an overfill detection/response time of FNU(.25,60) minutes (the operator notices that the fluid is not flowing).

USER INPUTS:

- System design

COMMENTS:

- This event is only important for systems for which pump-out is by flexible hose. For these tanks, this event is the only source of loss through a leaking outlet flange or gasket. For other tanks, losses by this mechanism will be overshadowed by losses through the same hole during normal discharge operations.

LABEL: A216

FAILURE: Inlet pipe rupture produces leaks during overfill events.

PROBABILITY DISTRIBUTION:

- Non-stochastic. This event will only occur if the inlet pipe has already ruptured under event B11.

PROBABILITY: See event B11 (pipe rupture).

VOLUME:

- The leak-rate calculations are similar to those used for event A213 (pump-out pipe rupture).

COMMENTS:

- Leakage from this pipe will also produce losses during normal filling. Cumulative losses from that mechanism will generally be much larger than losses occurring during overfill events.

LABEL: A217

FAILURE: Fill pipe corrosion produces losses during overflow events.

PROBABILITY DISTRIBUTION:

- Non-stochastic. This event will only occur if the fill pipe is already corroded leaking under event B13.

PROBABILITY: See event B13 (pipe corrosion).

VOLUME:

- The leak rate can be obtained from the geometry of event B13, using a static hydraulic head. The size of the corrosion hole is determined under event B13.

COMMENTS:

- Leakage from this hole will also produce losses during normal filling. Cumulative losses from that mechanism will generally be much larger than losses occurring during overfill events.

LABEL: A218

FAILURE: Inlet flange or gasket leaks during overfill events.

PROBABILITY DISTRIBUTION:

- Non-stochastic. This event will only occur if the inlet flange or gasket is already leaking under events B121 or B122.

PROBABILITY: See event B121 (flange leak) or B122 (gasket leak).

VOLUME:

- The leakage calculations are identical to those used for event A215 (outlet flange or gasket leak).

COMMENTS:

- Leakage from this flange or gasket will also produce losses during normal filling. The leak rate will be much higher during overflow, however, because the pressure will be much higher under the conditions of static hydraulic head that occur during overflow than it will be when fluid is in motion during normal filling. During normal filling, the pressure at this location is very low.

LABEL: A219

FAILURE: Vent pipe rupture produces losses during overfill events.

CALCULATIONS: See event B11 (pipe rupture).

PROBABILITY: See event B11.

VOLUME:

- The volume can be obtained from the system layout, using static hydraulic heads and sizing the rupture according to the method used for other pipe ruptures. See event B11.

LABEL: A220

FAILURE: Vent pipe corrosion produces losses during overfill events.

CALCULATIONS: See event B13 (pipe corrosion).

PROBABILITY: See event B13.

VOLUME:

- The volume can be obtained from the system layout, using static hydraulic heads and sizing the corrosion hole according to the method used for other pipe ruptures. See event B13.

LABEL: A221

FAILURE: Vent pipe flange leaks during overfill events.

CALCULATIONS: See event B121 (welded flange leaks).

PROBABILITY: See event B121.

VOLUME:

- The volume can be obtained from the system layout, using static hydraulic heads and sizing the flange leak according to the method used for other flange leaks. See event B13.

LABEL: B21

FAILURE: Asphalt Pad Breached

SOURCES: Conversations with local asphalt contractors.

ASSUMPTIONS:

- Breakage in a 2" pad with 6" class-5 base (a mixture of gravel, sand, and clay) will become general in an average of 8-12 years, depending on maintenance. It could occur as early as 3-5 years.
- A 3-4" pad with a crushed limestone base should last 15 years before generalized break-up begins.
- Break-up will occur earlier if the pad is not properly maintained.
- The entire spill volume is lost if the pad has broken up.

PROBABILITY DISTRIBUTION: Beta

PROBABILITY:

- For 2" pad, no maintenance, we use a beta distribution with a minimum value of 2.5 years, a mode of 8 years, and a maximum of 12 years.
- For a 2" pad, with maintenance, (or a 3-4" pad without maintenance) we use a beta distribution with parameters (4, 12, 15).
- For a 3-4" pad with maintenance, we use a beta distribution with parameters (5, 15, 18).

VOLUME: Entire volume of the spill.

LABEL: B31

FAILURE: Concrete Pad Breached

SOURCES:

- Telephone conversations with concrete contractors and officials in the Minnesota Department of Transportation.

PROBABILITY DISTRIBUTION: Normal

PROBABILITY: N(30,5)

VOLUME: Entire volume of spill.

LABEL: B33

FAILURE: Breach of Concrete Berm

ASSUMPTIONS:

- Concrete berms will age similarly to concrete pads (see event B31).

SOURCES: Event B31

PROBABILITY DISTRIBUTION: Normal

Probability: N(30,5)

VOLUME: Total spill volume.

LABEL: B41

FAILURE: Concrete Vault Fails

SOURCES:

- Best engineering judgment after converstations with concrete contractors.

PROBABILITY DISTRIBUTION: Normal

PROBABILITY: N(35,10)

VOLUME: Total volume of spill.

LABEL: B51

FAILURE: Synthetic Liner Fails

SOURCES:

- EPA, Liner Location Report (1984).

PROBABILITY DISTRIBUTION: Normal

PROBABILITY: N(35,10)

VOLUME: Total volume of spill.

HAZARDOUS WASTE TANKS

LABEL: ANUCAT(I,1)

FAILURE: Vehicle Crash

ASSUMPTIONS:

- This event is included in tank or pipe rupture (events T1124 and B11).

LABEL: ANUCAT (I,2) (aboveground or in-ground tanks only)

FAILURE: Vandalism of tank system resulting in total system loss.

ASSUMPTIONS:

- We assume that the probability of catastrophic release due to vandalism is of the same order of magnitude as the probability of catastrophic release due to a vehicle crash.

SOURCES:

- SCS Engineers (1983), Figure 4-18, p. 4-29.
- JRB Associates (1982), Exhibit 3-5.

CALCULATIONS:

- $< 1 \times 10^{-10}$/hr = failure rate for vehicle crash (JRB).
- 10^{-10}/hr = $(1 \times 10^{-10}$/hr)(24 hr/day)(365 day/yr) = 10^{-6}/yr.

PROBABILITY: 1×10^{-6}/yr

PROBABILITY DISTRIBUTION: Binomial

VOLUME: Entire tank contents.

LABEL: ANUCAT (I,3)

FAILURE: Tornado/hurricane (i.e. high wind storm event) resulting in total system loss (above-ground or in-ground tanks only).

ASSUMPTIONS:

- The facility is in coastal area subject to periodic hurricanes or in a tornado-prone area.
- The annual probability of a great hurricane (winds exceeding 125 mph) for 50-mile segments along the U. S. coastline ranges from 1% to 7% (Petak and Atkisson).
- Assume 20% damage for hurricanes with wind speeds of 125 mph (Petak and Atkisson).
- Assume an average of 2.5 tornado strikes per 10,000 square miles for the continental U.S. (U.S. Weather Bureau).
- Approximately 35% of all tornadoes have a Fujita classification of F2 or above (135 - 290 mph) (Petak and Atkisson).
- Assume approximately 50% damage for structures affected by tornadoes with a Fujita classification of F2 or above (Petak and Atkisson).
- Assume a facility has an area of approximately 10 acres.
- Assume that the average tornado strike is 2 mi x 300 yards = 200 acres. (U.S. Weather Bureau.)

SOURCES:

- Petak, William J. and Arthur A. Atkisson, Natural Hazard Risk Assessment and Public Policy: Anticipating the Unexpected, Springer-Verlag, New York (1982).
- United States Weather Bureau, Minneapolis Office, Personal Communication.

CALCULATIONS:

- 7% annual probability of hurricanes x 20% chance of damage = 1.4% chance of a damage due to a hurricane.

- (2.5/10,000) tornado strikes per square mile x (200 acres/strike) x (1mi^2/640 acres) x 10 acres/facility x (.35 x .5) probability of damage = 1.5×10^{-4}/yr per facility.

PROBABILITY:

- 0.014/yr for hurricanes
- 1.5×10^{-4}/yr for tornadoes

PROBABILITY DISTRIBUTION: Binomial

VOLUME: Entire tank contents

USER INPUTS:

- Is facility in a tornado zone?
- Is facility in a hurricane zone?

COMMENTS: This event only applies for above-ground or in-ground facilities.

LABEL: ANUCAT (I,4)

FAILURE: Earthquake causes total system loss.

ASSUMPTIONS:

- The facility is located in a seismically active area. Recurrence intervals for damaging earthquakes in Los Angeles and San Francisco areas are between 100 and 125 years.
- Assume .5 - 15% damage to commercial structures (built in California after 1933) in response to an earthquake with intensity of 7 or above.

SOURCES:

- California Institute of Technology (personal communication).

CALCULATIONS:

- (1/125) earthquakes per year x 10% average probability of damage $= 8 \times 10^{-4}$ damaging earthquakes per year.

PROBABILITY: .0008/yr

PROBABILITY DISTRIBUTIONS: Binomial

VOLUME: Entire tank contents

USER INPUTS:

- Is facility in a seismically active area?

HAZARDOUS WASTE TANKS

LABEL: ANUCAT (I,5)

FAILURE: Flood causes total system loss (above- or in-ground tanks only).

ASSUMPTIONS:

- The facility is located in a flood prone area.
- The facility is designed to withstand up to a 100-year flood.

SOURCES:

- Thomas Dunne and Luna Leopold, Water in Environmental Planning, W. H. Freeman and Company, San Francisco (1978).
- William J. Petak and Arthur A. Atkisson, Natural Hazard Risk Assessment and Public Policy: Anticipating the Unexpected, Springer-Verlag, New York (1982).

CALCULATIONS:

- According to Petak and Atkisson there is a 50% chance that a flood will result in damage to an above-ground tank.
- There is a 1% chance per year of a 100-year flood.
- 1% x 50% = .5%

PROBABILITY: .005/yr

PROBABILITY DISTRIBUTION: Binomial

VOLUME: Entire contents of tank.

USER INPUT:

Is facility located in a flood-prone area?

COMMENTS: This event applies only for above- or in-ground facilities.

LABEL: ANUCAT (I,6)

FAILURE: Ignition source available to ignite waste in tank system (all systems).

ASSUMPTIONS:

- The tank is properly grounded.
- The operator is reasonably cautious in handling the waste.

PROBABILITY: 1×10^{-6}/yr

PROBABILITY DISTRIBUTION: Binomial

VOLUME: Entire tank contents

COMMENTS:

- This event applies if the waste itself is the source of the fire. If the tank is ruptured by a nearby fire or explosion, ANUCAT (I,7) applies.
- This event applies only if the waste is flammable.

LABEL: ANUCAT (I,7)

FAILURE: Nearby fire or explosion causes complete system loss.

ASSUMPTIONS:

- A nearby fire or explosion is 1/3 as likely to damage an underground tank as it is to damage an above-ground tank.

SOURCES:

- JRB Associates (1982), Exhibit 3-5

CALCULATIONS:

- 3×10^{-7}/hr - probability of nearby fire (JRB)
- $(3 \times 10^{-7}/hr)(24\ hr/day)(365\ days/yr) = 2.6 \times 10^{-3}/yr$

PROBABILITY:

- 3×10^{-3}/yr (above-ground or in-ground) tank
- 1×10^{-3}/yr (below-ground tank)

PROBABILITY DISTRIBUTION: Binomial

VOLUME: Entire tank contents

LABEL: LIFDEF (I,1) and LIFDEF (I,2)

FAILURE: Vibrational/tortional stress causes rupture due to inadequate support or due to a construction defect.

ASSUMPTIONS:

- The only part of the system subject to vibration is the pump.
- We assume that these losses are included in pipe rupture (event B11).

PROBABILITY: Zero. This loss mechanism is included in event A1113.

LABEL: LIFDEF (I,3)

FAILURE: Inspection fails to detect installation damage or fabrication errors.

ASSUMPTIONS:

- Assume four levels of inspection/testing:
  1) none
  2) low--visual inspection
  3) medium--visual inspection and weld testing
  4) high--visual inspection, weld testing, and tightness testing

SOURCES:

- Best engineering judgment based on human error probabilities listed in Nuclear Regulatory Commission, Reactor Safety Study (1975)

PROBABILITY (by inspection level):

None - 1.00
Low - 0.50
Medium - 0.25
High - 0.05

PROBABILITY DISTRIBUTION: Binomial

USER INPUTS:

- Level of inspection or testing.

LABEL: LIFDEF (I,4)

FAILURE: Off-spec materials used in construction.

ASSUMPTIONS:

- Use of poor-grade materials would accelerate the onset of various leaks and ruptures. Since our probability distributions for these events are based on empirical data (the API/SCS survey) we assume that these probability distributions already account for off-spec materials.

LABEL: LIFDEF (I,5)A

FAILURE: Tank damaged during installation.

SOURCES:

- Best engineering judgment

PROBABILITY: 2×10^{-2}

PROBABILITY DISTRIBUTION: Binomial

VOLUME:

- We assume that the damage is similar to a seam leak.
- The volume will therefore be identical to volume loss from seam leaks (see event T1124). Leakage will begin in year 1.

VARIATIONS:

- Concrete and Stainless Steel Tanks. Since steel and stainless steel are approximately the same strength, we assume that stainless steel is just as vulnerable to installation damage as is steel. Based on conversations with concrete contractors, we assume that concrete also has a 2% chance of cracking due to improper installation.
- Fiberglass tanks. Fiberglass tanks are twice as likely to rupture as are steel tanks (see event T1124). We therefore assume that they are also twice as vulnerable to installation damage.

COMMENTS:

- Due to a transcription error, we used a value of .03 for the installation damage probability for steel, stainless steel, and concrete. This error did not substantially alter our results. It will be corrected in subsequent versions of the model.

LABEL: LIFDEF (I,5)B

FAILURE: Underground piping damaged during installation.

SOURCES: Best engineering judgment

PROBABILITY: 1×10^{-2}

PROBABILITY DISTRIBUTION: Binomial

VOLUME:

- We assume that the damage is similar to that from a pipe rupture.
- The leak rate will therefore be identical to that from event B11. Loss will begin in year 1.

VARIATIONS:

- Stainless steel pipes. Since steel and stainless steel are approximately the same strength, we assume that they are equally vulnerable to installation damage.
- Fiberglass pipes. Fiberglass is twice as likely to rupture as is steel (see event T1124). We therefore assume that fiberglass pipes have an installation-damage probability of 2×10^{-2}.

LABEL: LIFDEF (I,5)C

FAILURE: Above-ground piping damaged during installation.

SOURCES: Best engineering judgment

PROBABILITY: 1×10^{-2}

PROBABILITY DISTRIBUTION: Binomial

VOLUME:

- The leak rate is the same as that from an above-ground pipe rupture (see event B11).
- Leakage will begin in year 1.

VARIATIONS:

- Stainless steel pipes. Since steel and stainless steel are approximately the same strength, we assume that they are equally vulnerable to installation damage.
- Fiberglass pipes. Fiberglass is twice as likely to rupture as is steel (see event T1124). We therefore assuem that fiberglass pipes have an installation-damage probability of 2×10^{-2}.

LABEL: LIFDEF (I,5)D

FAILURE: Welded flange damaged during installation.

SOURCES:

- Best engineering judgment

PROBABILITY: 2×10^{-2}

PROBABILITY DISTRIBUTION: Binomial

VOLUME:

- We assume that the leak rate is the same as that for a welded flange leak (event B121).
- Leakage will begin in year 1.

LABEL: LIFDEF (I,5)E

FAILURE: Gasket damaged during installation (or improperly installed).

SOURCES:

- Best engineering judgment

PROBABILITY: 1.5×10^{-2}

PROBABILITY DISTRIBUTION: Binomial

VOLUME:

- We assume that the leak rate is the same as that for a gasket failure (event B122).
- Leakage begins in year 1.

LABEL: LIFDEF (I,6) and (I,7)

FAILURE: Stresses due to settling.

ASSUMPTIONS: This event is already included in tank and piping ruptures.

LABEL: FLVCN1

FAILURE: Automatic level controller fails.

ASSUMPTIONS:

- Assume that the failure of the controller, the controller settings, and the impulse lines may each cause controller malfunction

SOURCES:

- Anyakora, Engel and Lees, Table V, p. 400

CALCULATIONS:

- 0.29/yr = 7.9×10^{-4}/dy = controller failure rate (Anyakora, Engel and Lees).
- 0.14/yr = 3.8×10^{-4}/dy = controller settings failure rate (Anyakora, Engel and Lees).
- 0.77/yr = 2.1×10^{-3}/dy = impulse lines failure rate (Anyakora, Engel and Lees).
- $7.9 \times 10^{-4} + 3.8 \times 10^{-4} + 2.1 \times 10^{-3} = 3.3 \times 10^{-3}$/dy
- 3.3×10^{-3}/dy = 9.4×10^{-2}/mo

PROBABILITY DISTRIBUTION: Binomial

PROBABILITY: 9.4×10^{-2}/mo

LABEL: FLVCN2

FAILURE: Emergency shut-off level controller fails to function.

ASSUMPTIONS:

- We assume that the emergency shut-off controller is inspected monthly.

SOURCES: See event FLVCN1

CALCULATIONS:

- According to event FLVCN1, the probability of automatic level controller failure is 9.4×10^{-2}/mo.
- If the level controller is inspected monthly, then the average failure lasts half a month. The probability that the controller is in a failed state at any given time is therefore $.5 \times 9.4 \times 10^{-2}$, which is approximately 5×10^{-2}.

PROBABILITY DISTRIBUTION: Binomial

PROBABILITY: .05/Demand

LABEL: LEVIN2

FAILURE: Emergency shut-off level sensor fails to function.

ASSUMPTIONS:

- We assume that the published failure rates include failures in the meter, the sensor, and the impulse lines.
- We assume that the emergency shut-off level sensor is inspected monthly.

SOURCES:

- Anyakora, Engel, and Lees (1971), Table V, p. 400.

CALCULATIONS:

- .2/yr = failure rate for a capacitance-type level transducer (Anyakora, Engel and Lees).
- .2/yr = 5.5×10^{-4}/day = 1.6×10^{-2}/mo.
- If the level controller is inspected monthly, then the average failure lasts half a month. The probability that the controller is in a failed state at any given time is therefore $.5 \times 1.6 \times 10^{-2}$, which is 8×10^{-3}.

PROBABILITY DISTRIBUTION: Binomial

PROBABILITY: 8×10^{-3} .

COMMENTS:

- Due to a transcription error, this event's probability was set to the probability calculated for event FLVCN2. The result was a conservative error but the number will be changed to the value calculated above in future versions of the model.

LABEL: MOALARM

FAILURE: High liquid level alarm system failure.

ASSUMPTIONS:

- We assume that the high level alarm is tested once per year. Thus, the average alarm failure will persist for 6 months.

SOURCES:

- Lawley (1974), p. 54, note 6.

CALCULATIONS:

- 0.2/yr = frequency of dangerous high level alarm failures (Lawley).
- 6 months = duration of average undetected failure.
- 0.2 (6/12) = 0.1 = fractional dead time for high level alarm.

PROBABILITY: .1/demand

PROBABILITY DISTRIBUTION: Binomial

COMMENTS:

- The same failure probability applies to leak detectors in vaulted tanks or interstitial alarms in double-walled tanks or pipes.
- We also model interstitial alarms according to this probability distribution. Many of these alarms, however, have status lights which can be checked at any desired frequency. Thus, if status is checked conscientiously, the per-demand failure probability may be considerably lower. Our value of 10% is therefore a conservative estimate.

HAZARDOUS WASTE TANKS

LABEL: MOFILL

FAILURE: Tank is to be filled nearly to capacity.

ASSUMPTIONS:

- Treatment tanks are always filled to their operating capacities.
- We assume that pump-out schedules for storage or accumulation tanks generally allow sufficient margin for error that the tank is not filled completely to capacity unless something interferes with the normal pump-out schedule or there is an unexpected upsurge in the generation of waste. We conservatively assume that this happens once per year.

CALCULATIONS:

- 1 per year = .0027 per day = $1 - (1-.0027)^{30}$ = .079 per month.

PROBABILITY DISTRIBUTION: Binomial

PROBABILITY:

- 1.00 for treatment tanks.
- .079/mo. for storage or accumulation tanks.

LABEL: MOLEVIN

FAILURE: Level indicator malfunction results in attempted overfill.

ASSUMPTIONS:

- We assume that the published failure rates include failures in the meter, the sensor, and the impulse lines.
- We assume that a fault is detected and repaired after one faulty transfer.

SOURCES:

- Anyakora, Engel, and Lees (1971), Table V, p. 400.

CALCULATIONS:

- .22/yr = failure rate for a capacitance-type level transducer (Anyakara, Engel, and Lees).
- .22 x .5 = .1/yr = rate of overfill events due to level transducer failure.
- $.2/yr = 5.5 \times 10^{-4}/day = 1-(1-5.5 \times 10^{-4})^{30}/mo.$

PROBABILITY DISTRIBUTION: Binomial

PROBABILITY: .16/mo.

VOLUME:

- Assume that the overflow consists of between 0 and 100% of a batch. Thus Q = FNU(0, volume of one batch).

USER INPUTS:

- Volume transferred per batch

COMMENT:

- Due to a round-off error our model uses a probability of .15/mo. The difference between this and the correct value is not significant.

LABEL: MOPMCE

FAILURE: Outlet pump fails to start on demand (extreme environment)

ASSUMPTIONS:

- 75% of pump failures are failures to start. The remaining 25% are failures to run under event MOPMOE

SOURCES:

- Nuclear Regulatory Commission, Reactor Safety Study (1975), Table III 2-3.
- Southwest Research Institute (1982).
- Henley and Kumamoto (1981), Figure 6.7, p. 278.

CALCULATIONS:

- 1×10^{-4} to 1×10^{-3} per operating hour = probability of pump failure in extreme environment (Reactor Safety Study)
- The geometric mean of this range of values = 3×10^{-4} per operating hour.
- $(3 \times 10^{-4}/hr)(.75) = 2.25 \times 10^{-4}$ per operating hour = probability that pump fails to run.
- We convert this per-hour probability into a per-demand probability. We do this by noting that the pump must have started properly when the previous batch drained. Otherwise, the operator would have noticed the failure and repaired it. Thus, if the pump fails, it does so during the fill time for the present batch. The probability of this is given by:

$$(2 \times 10^{-4} \times \text{fill time})$$

PROBABILITY DISTRIBUTION: Binomial

PROBABILITY: $(2 \times 10^{-4} \times \text{fill time per batch})$ per demand.

USER INPUTS:

- The per-batch fill time

COMMENTS:

- For continuous systems, the fill time is the entire operating day.
- Due to a round-off error our model uses a probability of 3×10^{-4} x fill time per batch. The difference between this and the correct value is not significant.

LABEL: MOPMCN

FAILURE: Outlet pump fails to start on demand (normal environment)

ASSUMPTIONS:

- 75% of pump failures are failure to start. The remaining 25% are failures to run under event MOPMON.

SOURCES:

- Nuclear Regulatory Commission, Reactor Safety Study (1975), Table III 2-3.
- Southwest Research Institute (1982).
- Henley and Kumamato (1981), Figure 6.7, p. 278.

CALCULATIONS:

- 1×10^{-6} to 1×10^{-5} per operating hour = probability of pump failure in normal environment (Reactor Safety Study).
- The geometric mean of this range of values = 3×10^{-6} per operating hour.
- $(3 \times 10^{-6}/hr)(.75) = 2.25 \times 10^{-6}$ per operating hour = probability that pump fails to run.
- We convert this per-hour probability into a per-demand probability. We do this by noting that the pump must have started properly when the previous batch drained. Otherwise, the operator would have noticed the failure and repaired it. Thus, if the pump fails, it does so during the fill time for the present batch. The probability of this is given by:

$$(2 \times 10^{-6} \times \text{fill time})$$

PROBABILITY DISTRIBUTION: Binomial

PROBABILITY: (2×10^{-6} x fill time per batch) per demand.

USER INPUTS:

- The per-batch fill time

COMMENTS:

- For continuous systems, the fill time is the entire operating day.
- Due to a round-off error our model uses a probability of 3×10^{-6} x fill time per batch. The difference between this and the correct value is not significant.

LABEL: MOPMOE

FAILURE: Pump fails in "on" position, preventing emergency shut-off (extreme environment).

ASSUMPTIONS:

- Assume that failure of the solenoid or the controller can cause a pump to fail in the open position. We assume that these subcomponent failures make up approximately 25% of all pump malfunctions.

SOURCES:

- Nuclear Regulatory Commission, Reactor Safety Study (1975).
- Southwest Research Institute (1982).
- Henley and Kumamoto (1981), Figure 6.7, p. 278.

CALCULATIONS:

- 1×10^{-4} to 1×10^{-3} per operating hour = probability of pump failure in extreme environment (Reactor Safety Study).
- The geometric mean of this range of values = 3×10^{-4} per operating hour.
- $(3 \times 10^{-4}/hr)$ (.25) = 7.5×10^{-5} per operating hour = probability that the pump fails in the "on" position.
- We need to convert this per-hour probability into a per-demand probability. We do this by noting that the pump must have shut off properly after the previous batch finished filling. Otherwise, the operator would have noticed the failure and repaired it. Thus, if the pump fails it does so during the fill time for the present batch. The probability of this is given by:

$$(7.5 \times 10^{-5} \times \text{fill time})$$

PROBABILITY DISTRIBUTION: Binomial

PROBABILITY: $(7.5 \times 10^{-5}$ x fill time per batch) per demand

USER INPUTS:

- The per-batch fill time

COMMENTS:

- For continuous systems, the fill time is the entire operating day.

LABEL: MOPMON

FAILURE: Pump fails in "on" position, preventing emergency shut-off (normal environment).

ASSUMPTIONS:

- Assume that failure of the solenoid or the controller can cause a pump to fail in the open position. We assume that these subcomponent failures make up approximately 25% of all pump malfunctions.

SOURCES:

- Nuclear Regulatory Commission, Reactor Safety Study (1975).
- Southwest Research Institute (1982).
- Henley and Komamoto (1981), Figure 6.7, p. 278.

CALCULATIONS:

- 1×10^{-7} to 1×10^{-4} per operating hour = probability of pump failure in normal environment (Reactor Safety Study).
- The geometric mean of this range of values = 3×10^{-6} per operating hour.
- $(3 \times 10^{-6}/\text{hr})(.25) = 7.5 \times 10^{-7}$ per operating hour = probability that the pump fails in the "on" position.
- We convert this per-hour probability into a per-demand probability in the same way that we do for pumps in an extreme environment (event MOPMOE). Thus, the probability is given by:

$$(7.5 \times 10^{-7} \times \text{fill time})$$

PROBABILITY DISTRIBUTION: Binomial

PROBABILITY: $(7.5 \times 10^{-7} \times$ fill time per batch) per demand

USER INPUTS:

- The per-batch fill time

COMMENTS:

- For continuous system, the fill time is the entire operating day.

LABEL: MOVLCE

FAILURE: Outlet valve fails in the closed position, preventing emergency shut-off (extreme environment).

ASSUMPTIONS:

- We assume that 50% of valve failures occur in the closed position.

SOURCES:

- Anyakora, Engel, and Lees (1971), Table V.
- Southwest Research Institute (1982), Table 2, p. 32.
- Henley and Kumamoto (1981), Figure 6.7, p. 278.
- Nuclear Regulatory Commission, Reactor Safety Study, (1975), Table III-2-3.

CALCULATIONS:

- 0.60/yr = expected number of control valve failures in a normal environment. (Anyakora, Engel and Lees (1971).
- Valve failures are 10 times more common in extreme than normal environments. (Source, best engineering judgment based on Henley and Kumamoto (1981) and Reactor Safety Study). Therefore, 6.0/yr = the expected number of control valve failures in an extreme environment.
- If 50% of these failures occur in the closed position, then 3.0/yr = the expected number of control valves failing in the closed position.
- $3.0/yr = 3.4 \times 10^{-4}/hr$
- Since the valve must have been functional at the time the previous batch drained, this event can only occur if failure occurs during the time when the tank is being filled. Thus, the per demand failure probability is given by:

$$(3.4 \times 10^{-4}) \times (\text{fill time per batch})$$

PROBABILITY DISTRIBUTION: Binomial (per demand)

PROBABILITY: $(3.4 \times 10^{-4}) \times$ (fill time per batch) per demand

USER INPUTS:

- Fill time per batch
- Number of operating hours per day

COMMENTS:

- For continuous systems, the fill time is the entire operating day.

LABEL: MOVLCN

FAILURE: Outlet valve fails in the closed position, preventing emergency shut-off (normal environment).

ASSUMPTIONS:

- Failures are only 10% as likely in normal as extreme environments (see sources cited under event MOVLCE).

SOURCES: See event MOVLCE

CALCULATIONS:

- The per demand probability of failure in an extreme environment is 3.4×10^{-4} x (fill time per batch). See event MOVLCE.

PROBABILITY DISTRIBUTION: Binomial (per demand)

PROBABILITY: (3.4×10^{-4}) x (fill time per batch)

USER INPUTS:

- Fill time per batch
- Number of operating hours per day

COMMENTS:

- For continuous systems, the fill time is the entire operating day.

LABEL: MOVLOE

FAILURE: Inlet valve fails in the open position, preventing emergency shut-off (extreme environment).

ASSUMPTIONS:

- Assume that 50% of valve failures occur in the open position.

SOURCES:

- Anyakora, Engel, and Lees (1971), Table V.
- Southwest Research Institute (1982), Table 2, p. 32.
- Henley and Kumamoto (1981), Figure 6.7, p. 278.
- Nuclear Regulatory Commission, Reactor Safety Study (1975) Table III-2-3.

CALCULATIONS:

- 0.60/yr = expected number of control valve failures in a normal environment (Anyakora, Engel and Lees (1971)).
- Valve failures are 10 times more common in extreme than normal environments. (Source, best engineering judgment based on Henley and Kumamoto (1981) and Reactor Safety Study). Therefore, 6.0/yr = the expected number of control valve failures in an extreme environment.
- If 50% of these failures occur in the open position, then 3.0/yr = the expected number of control valves failing in the open position.
- 3.0/yr = 3.4×10^{-4}/hr.
- Since the valve must have been functional at the time the batch began to fill, this event can only occur if failure occurs during the time when the tank is being filled. Thus, the per demand failure probability is (3.4×10^{-4}) x (fill time per batch).

PROBABILITY DISTRIBUTION: Binomial (per demand)

PROBABILITY: (3.4×10^{-4}) x (fill time per batch)

USER INPUTS:

- Fill time per batch
- Number of operating hours per day

COMMENTS:

- For continuous systems, the fill time is the entire operating day.
- This event can also cause an attempted overfill. We only model this form of attempted overfill for gravity-fed systems, however, because for pump-fed systems, the failure can be remedied by shutting off the pump. In theory, the pump could also fail in the "on" position, causing an attempted overfill even for pump-fed systems, but such simultaneous failure is extremely unlikely, and is overshadowed by the other types of failure (e.g. operator error) which are more likely to cause attempted overflows.

LABEL: MOVLON

FAILURE: Inlet valve fails in the open position, preventing emergency shut-off (normal environment).

ASSUMPTIONS:

- Failures are only 10% as likely in normal as extreme environments (see sources cited under event MOVLOE).

SOURCES: See event MOVLOE

CALCULATIONS:

- The per demand probability of failure in an extreme environment is $(3.4 \times 10^{-4}) \times$ (fill time per batch). See event MOVLOE.

PROBABILITY DISTRIBUTION: Binomial (per demand)

PROBABILITY: $(3.4 \times 10^{-5}) \times$ (fill time per batch)

USER INPUTS:

- Fill time per batch
- Number of operating hours per day

COMMENTS:

- For continuous systems, the fill time is the entire operating day.
- This event can also cause an attempted overfill. We only model this form of attempted overfill for gravity-fed systems, however, because for pump-fed systems, the failure can be remedied by shutting off the pump. In theory, the pump could also fail in the "on" position, causing an attempted overfill even for pump-fed systems, but such simultaneous failure is extremely unlikely, and is overshadowed by the other types of failure (e.g. operator error) which are more likely to cause attempted overflows.

HAZARDOUS WASTE TANKS

LABEL: OFTROM

FAILURE: Operator fails to respond to high level alarm.

ASSUMPTIONS:

- Failure may be due to failure to hear alarm, failure to take corrective action, or inability to take corrective action.

SOURCES:

- Lawley (1974), p. 54, note 7.

PROBABILITY DISTRIBUTION: Binomial

PROBABILITY: 3×10^{-2}/demand

LABEL: OFTRCOM

FAILURE: Operator erroneously responds to high level alarm.

ASSUMPTIONS:

- At the time when the alarm first sounds, the operator feels no sense of panic. He responds in a routine manner.

SOURCES:

- Nuclear Regulatory Commission, Reactor Safety Study (1975).

CALCULATIONS:

- 3×10^{-3}/demand = probability of human error of commission (selecting wrong switch, etc.), Reactor Safety Study, Table III 6-1.

PROBABILITY DISTRIBUTION: Binomial

PROBABILITY: 3×10^{-3}/demand

COMMENTS:

- If the operator panics, the probability of error will be much higher. The Reactor Safety Study gives an error rate of 20-30% for trained personnel under high stress levels where dangerous activities are occurring rapidly.

LABEL: OPCOMM

FAILURE: Operator error in batch start-up leads to attempted overfill.

ASSUMPTIONS:

- Operate action is required to initiate the transfer of fluid at the start of each batch. Mistakes may result in an attempt to transfer too much fluid.
- Operator action is also necessary whenever a continuous process is started up. We assume that this occurs once per operating day.

SOURCES:

- Nuclear Regulatory Commission (1975)

CALCULATIONS:

- 3×10^{-3}/demand = estimated rate of human errors of commission (e.g. selecting a wrong switch). Source: Nuclear Regulatory Commission.
- Let n be the number of batches per day. (Let n = 1 for continuous systems).
- Then the probability that the operator makes no errors is $1-3 \times 10^{-3}$ per batch, or

$$(1-.003)^{30n}$$

per month. The probability of 1 or more errors is

$$1-(1-.003)^{30n}$$

per month.

- If n = 1 this value is .086/mo.

PROBABILITY DISTRIBUTION: Binomial

PROBABILITY:

- $1 - .997^{30n}$/mo for batch systems

- .086/mo for continuous systems

USER INPUTS:

- **Number of batches per day (n)**

LABEL: OPVLOE

FAILURE: Inlet valve fails to close, causing overflow (extreme/environment).

ASSUMPTIONS:

- This event only applies for automatic valves. Manual valves are very unlikely to fail since they have no automated components.

SOURCES: See event MOVLOE.

CALCULATIONS:

- According to event MOVLOE, the probability of such an event is 3.4×10^{-4}/hr.
- The probability of failure during any given batch is therefore $(T_b)(3.4 \times 10^{-4})$ where T_b is the fill time per batch.
- The probability of failure during any given month is

$$1-\left[1-T_b(3.4 \times 10^{-4})\right]^{n_b m}$$

where n_b is the number of batches per day, and m is the number of operating days per month. For continuous systems, n_b is 1 and T_b is the entire operating day.

PROBABILITY DISTRIBUTION: Binomial

PROBABILITY: $1-\left[1 - T_b(3.4 \times 10^{-4})\right]^{n_b m}$

USER INPUTS:

- Fill-time per batch (T_b)
- Number of batches per day (n_b)
- Number of operating day per month (m)

HAZARDOUS WASTE TANKS

LABEL: OPVLON

FAILURE: Inlet valve fails to close, causing overflow (normal environment)

ASSUMPTIONS:

- This event only applies for automatic valves. Manual valves are very unlikely to fail since they have no automated components.

SOURCES: See event MOVLON

CALCULATIONS:

- According to event MOVLON, the probability of such an event is 3.4 x 10^{-5}/hr.

- The probability of failure during any given failure is therefore $(T_b)(3.4 \times 10^{-5})$ where T_b is the fill time per batch.

- The probability of failure during any given month is

$$1- \left[1-T_b(3.4 \times 10^{-4})\right]^{n_b m}$$

where n_b is the number of batches per day, and m is the number of operating days per month. For continuous systems, n_b is 1 and T_b is the entire operating day.

PROBABILITY DISTRIBUTION: Binomial

PROBABILITY: $1- \left[1-T_b(3.4 \times 10^{-5})\right]^{n_b m}$

USER INPUTS:

- Fill-time per batch (T_b)
- Number of batches per day (n_b)
- Number of operating days per month (m)

HAZARDOUS WASTE TANKS

LABEL: PADINSF, VLTINSF, CRBINSF

FAILURE: Visual inspection fails to detect secondary containment failure (pad, vault, curb)

ASSUMPTIONS:

- We assume that this visual inspection is a passive "walk-around."
- We assume that the visual inspection is infrequent enough that it does not become monotonously routine to the operator.

SOURCES:

- Best engineering judgment based on Nuclear Regulatory Commission, Reactor Safety Study (1975), and Lawley (1974).

PROBABILITY DISTRIBUTION: Binomial

PROBABILITY: .1

COMMENTS:

- For simplicity, we assume that all secondary-containment failures occur at the beginning of the month and that they are repaired immediately after detection. Thus, the secondary-containment system is in a failed state for a minimum of one complete month. A similar result would be obtained by assuming that cracks occur in the middle of the inspection cycle, and that repair takes two weeks.
- We assume that all secondary-containment inspections are statistically independent events. Thus a failure to detect a breach in a vault does not influence the probability that the inspector will also fail to detect a breach in a pad or curb. Similarly, a failure to detect a fault in one month does not change the probability that it will be detected during the next inspection.

APPENDIX B

Statistical Analysis of PACE Tank Corrosion Data

INTRODUCTION

A group of Canadian oil companies, working through the Petroleum Association for Conservation of the Canadian Environment (PACE) have compiled data on 300 underground gasoline storage tanks.[1] It is unclear what sampling techniques were used to select the 300 tanks, but it appears that the intent was to obtain a "snapshot" of the contemporary situation. It is not clear whether the data distinguishes interior and exterior corrosion, but since the intent was to determine the effect of soil variations on tank leakage, it must be assumed that the survey focused on exterior corrosion. The Canadian survey therefore represents raw data distinct from the API tank leak survey[2] and independent from either Warren Rogers'[3] preliminary or revised statistical model.

In raw form, these data are presented in Figures 1 and 2.[4] They consist of scatter diagrams of tank age and "Soil Aggressiveness Values" (SAV) for 108 leaking tanks and 192 non-leaking tanks. Each dot on the scatter diagrams represents one or more tanks, with overlapping points tallied by the small numerals adjacent to the relevant dots. Numerical listings of all 300 points are presented in Tables 1, 2, 3, and 4.

SAV is calculated according to the formula depicted in Figure 3. It is designed to incorporate soil resistivity, pH, moisture content, and sulfides, as well as the effect of variations in resistivity and pH over the tank installation site. The resultant numerical index is designed to present a cardinal ranking of soil

---

[1]This data is discussed in PACE, "Underground Tank Systems: Review of State of the Art and Guidelines," PACE report No. 82-3, Ottawa (1983).

[2]American Petroleum Institute, Tank and Piping Leak Survey, 1977 to 1980.

[3]Warren Rogers Associates, Inc., "Prediction of Leaks in Unprotected Steel Storage Tanks," included in correspondence package from Betsy Tam, EPA to Chris Lough, PRA.

[4]These data were provided by Esso Petroleum, Canada. Esso Canada participated in the PACE study.

FIGURE 1

LEAKING TANK CHART

AGE VS. SOIL AGGRESSIVENESS

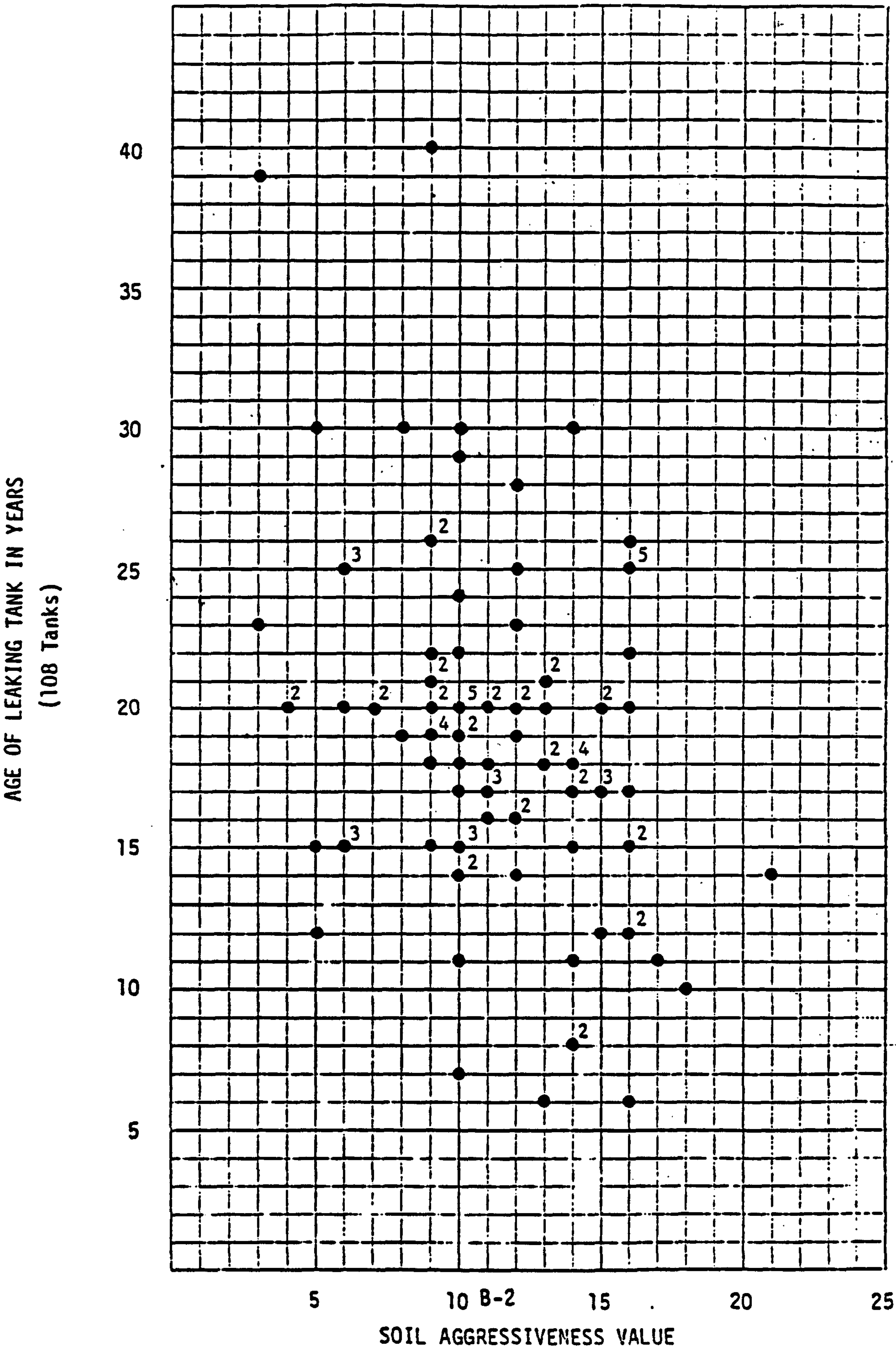


FIGURE 2

TASK FORCE NON-LEAKING TANK CHART

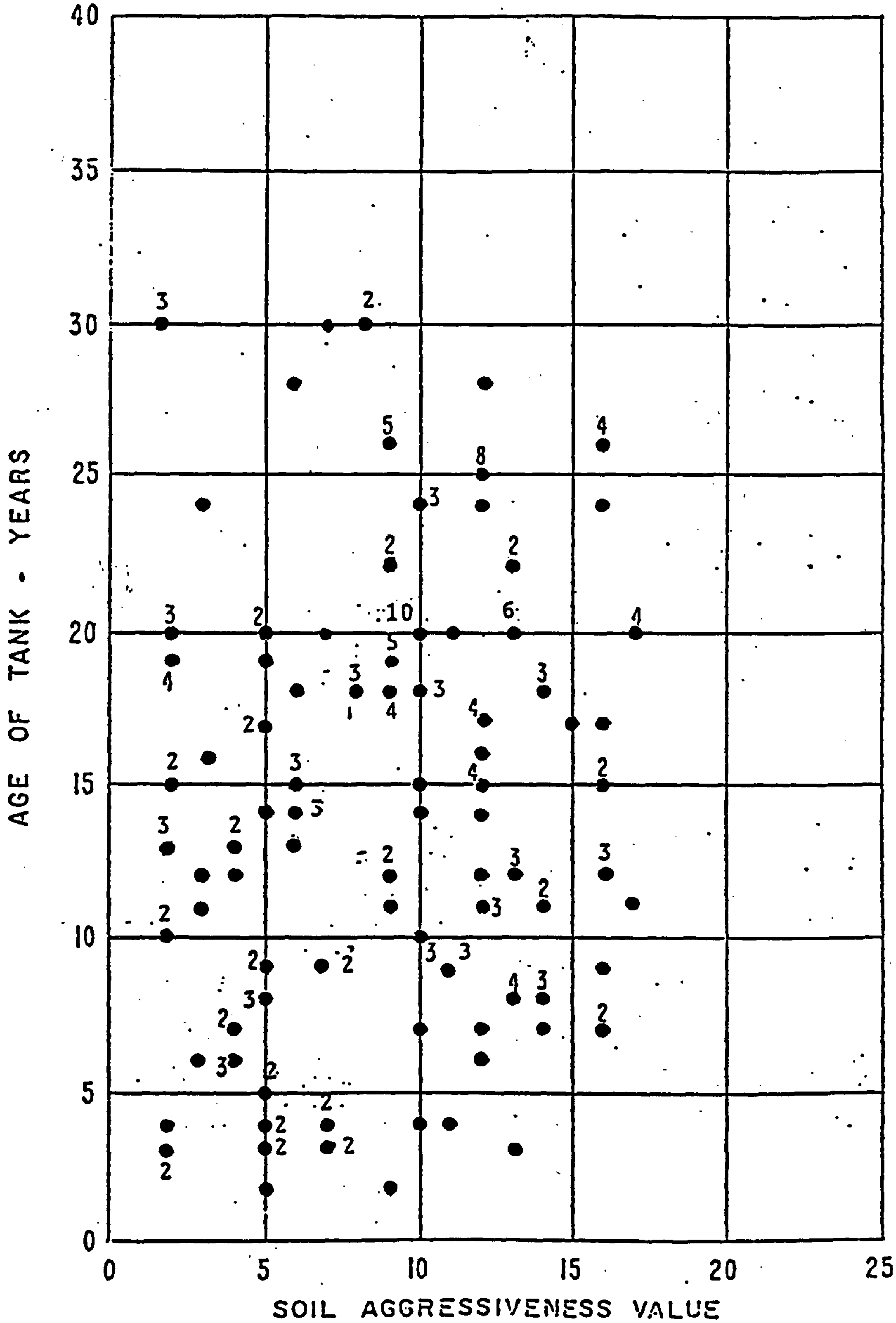


TABLE 1

Soil Aggressiveness Values (SAV) and ages for leaking tanks.

Leaking tanks			Leaking tanks			Leaking tanks		
SAV	Age	Age*SAV	SAV	Age	Age*SAV	SAV	Age	Age*SAV
5	12	60	9	21	189	10	30	300
3	23	69	10	19	190	16	20	320
10	7	70	10	19	190	12	28	336
5	15	75	16	12	192	16	22	352
13	6	78	16	12	192	9	40	360
4	20	80	12	16	192	16	25	400
4	20	80	12	16	192	16	25	400
6	15	90	11	18	198	16	25	400
6	15	90	9	22	198	16	25	400
6	15	90	10	20	200	16	25	400
16	6	96	10	20	200	16	26	416
10	11	110	10	20	200	14	30	420
14	8	112	10	20	200			
14	8	112	10	20	200			
3	39	117	14	15	210			
6	20	120	11	20	220			
9	15	135	11	20	220			
10	14	140	10	22	220			
10	14	140	12	19	228			
7	20	140	13	18	234			
7	20	140	13	18	234			
10	15	150	9	26	234			
10	15	150	9	26	234			
10	15	150	14	17	238			
6	25	150	14	17	238			
6	25	150	16	15	240			
6	25	150	16	15	240			
5	30	150	12	20	240			
8	19	152	12	20	240			
14	11	154	10	24	240			
9	18	162	8	30	240			
12	14	168	14	18	252			
10	17	170	14	18	252			
9	19	171	14	18	252			
9	19	171	14	18	252			
9	19	171	15	17	255			
9	19	171	15	17	255			
11	16	176	15	17	255			
18	10	180	13	20	260			
15	12	180	16	17	272			
10	18	180	13	21	273			
9	20	180	13	21	273			
9	20	180	12	23	276			
17	11	187	10	29	290			
11	17	187	21	14	294			
11	17	187	15	20	300			
11	17	187	15	20	300			
9	21	189	12	25	300			

TABLE 1

Soil Aggressiveness Values (SAV) and ages for leaking tanks.

Leaking tanks			Leaking tanks			Leaking tanks		
SAV	Age	Age*SAV	SAV	Age	Age*SAV	SAV	Age	Age*SAV
5	12	60	9	21	189	10	30	300
3	23	69	10	19	190	16	20	320
10	7	70	10	19	190	12	28	336
5	15	75	16	12	192	16	22	352
13	6	78	16	12	192	9	40	360
4	20	80	12	16	192	16	25	400
4	20	80	12	16	192	16	25	400
6	15	90	11	18	198	16	25	400
6	15	90	9	22	198	16	25	400
6	15	90	10	20	200	16	25	400
16	6	96	10	20	200	16	26	416
10	11	110	10	20	200	14	30	420
14	8	112	10	20	200			
14	8	112	10	20	200			
3	39	117	14	15	210			
6	20	120	11	20	220			
9	15	135	11	20	220			
10	14	140	10	22	220			
10	14	140	12	19	228			
7	20	140	13	18	234			
7	20	140	13	18	234			
10	15	150	9	26	234			
10	15	150	9	26	234			
10	15	150	14	17	238			
6	25	150	14	17	238			
6	25	150	16	15	240			
6	25	150	16	15	240			
5	30	150	12	20	240			
8	19	152	12	20	240			
14	11	154	10	24	240			
9	18	162	8	30	240			
12	14	168	14	18	252			
10	17	170	14	18	252			
9	19	171	14	18	252			
9	19	171	14	18	252			
9	19	171	15	17	255			
9	19	171	15	17	255			
11	16	176	15	17	255			
18	10	180	13	20	260			
15	12	180	16	17	272			
10	18	180	13	21	273			
9	20	180	13	21	273			
9	20	180	12	23	276			
17	11	187	10	29	290			
11	17	187	21	14	294			
11	17	187	15	20	300			
11	17	187	15	20	300			
9	21	189	12	25	300			

TABLE 2

Soil Aggressiveness Values (SAV) and ages for non-leaking tanks.

Non-leakers			Non-leakers			Non-leakers			Non-leakers		
SAV	Age	SAV*Age	SAV	Age	SAV*Age	SAV	Age	SAV*Age	SAV	Age	SAV*Age
2	3	6	4	13	52	16	9	144	12	17	204
2	3	6	2	30	60	12	12	144	12	17	204
2	4	8	2	30	60	8	18	144	7	30	210
5	2	10	2	30	60	8	18	144	11	20	220
5	3	15	7	9	63	8	18	144	9	26	234
5	3	15	7	9	63	10	15	150	9	26	234
9	2	18	10	7	70	14	11	154	9	26	234
3	6	18	5	14	70	14	11	154	9	26	234
5	4	20	12	6	72	13	12	156	9	26	234
5	4	20	3	24	72	13	12	156	16	15	240
2	10	20	6	13	78	13	12	156	16	15	240
2	10	20	12	7	84	9	18	162	10	24	240
7	3	21	6	14	84	9	18	162	10	24	240
7	3	21	6	14	84	9	18	162	10	24	240
4	6	24	6	14	84	9	18	162	8	30	240
4	6	24	5	17	85	12	14	168	8	30	240
4	6	24	5	17	85	6	28	168	14	18	252
5	5	25	6	15	90	9	19	171	14	18	252
5	5	25	6	15	90	9	19	171	14	18	252
2	13	26	6	15	90	9	19	171	15	17	255
2	13	26	5	19	95	9	19	171	13	20	260
2	13	26	14	7	98	9	19	171	13	20	260
7	4	28	11	9	99	12	15	180	13	20	260
7	4	28	11	9	99	12	15	180	13	20	260
4	7	28	11	9	99	12	15	180	13	20	260
4	7	28	9	11	99	12	15	180	13	20	260
2	15	30	10	10	100	10	18	180	16	17	272
2	15	30	10	10	100	10	18	180	13	22	286
3	11	33	10	10	100	10	18	180	13	22	286
3	12	36	5	20	100	17	11	187	12	24	288
2	19	38	5	20	100	16	12	192	12	25	300
2	19	38	13	8	104	16	12	192	12	25	300
2	19	38	13	8	104	16	12	192	12	25	300
2	19	38	13	8	104	12	16	192	12	25	300
13	3	39	13	8	104	9	22	198	12	25	300
10	4	40	9	12	108	9	22	198	12	25	300
5	8	40	9	12	108	10	20	200	12	25	300
5	8	40	6	18	108	10	20	200	12	25	300
5	8	40	16	7	112	10	20	200	12	28	336
2	20	40	16	7	112	10	20	200	17	20	340
2	20	40	14	8	112	10	20	200	17	20	340
2	20	40	14	8	112	10	20	200	17	20	340
11	4	44	14	8	112	10	20	200	17	20	340
5	9	45	12	11	132	10	20	200	16	24	384
5	9	45	12	11	132	10	20	200	16	26	416
4	12	48	12	11	132	10	20	200	16	26	416
3	16	48	10	14	140	12	17	204	16	26	416
4	13	52	7	20	140	12	17	204	16	26	416

TABLE 3

Soil Aggressiveness Values (SAV) and ages for leaking tanks.

Leaking tanks			Leaking tanks			Leaking tanks		
SAV	Age	Age*SAV	SAV	Age	Age*SAV	SAV	Age	Age*SAV
13	6	78	14	18	252	16	25	400
16	6	96	14	18	252	9	26	234
10	7	70	8	19	152	9	26	234
14	8	112	9	19	171	16	26	416
14	8	112	9	19	171	12	28	336
18	10	180	9	19	171	10	29	290
10	11	110	9	19	171	5	30	150
14	11	154	10	19	190	8	30	240
17	11	187	10	19	190	10	30	300
5	12	60	12	19	228	14	30	420
15	12	180	4	20	80	3	39	117
16	12	192	4	20	80	9	40	360
16	12	192	6	20	120			
10	14	140	7	20	140			
10	14	140	7	20	140			
12	14	168	9	20	180			
21	14	294	9	20	180			
5	15	75	10	20	200			
6	15	90	10	20	200			
6	15	90	10	20	200			
6	15	90	10	20	200			
9	15	135	10	20	200			
10	15	150	11	20	220			
10	15	150	11	20	220			
10	15	150	12	20	240			
14	15	210	12	20	240			
16	15	240	13	20	260			
16	15	240	15	20	300			
11	16	176	15	20	300			
12	16	192	16	20	320			
12	16	192	9	21	189			
10	17	170	9	21	189			
11	17	187	13	21	273			
11	17	187	13	21	273			
11	17	187	9	22	198			
14	17	238	10	22	220			
14	17	238	16	22	352			
15	17	255	3	23	69			
15	17	255	12	23	276			
15	17	255	10	24	240			
16	17	272	6	25	150			
9	18	162	6	25	150			
10	18	180	6	25	150			
11	18	198	12	25	300			
13	18	234	16	25	400			
13	18	234	16	25	400			
14	18	252	16	25	400			
14	18	252	16	25	400			

TABLE 3

Soil Aggressiveness Values (SAV) and ages for leaking tanks.

Leaking tanks

SAV	Age	Age*SAV
13	6	78
16	6	96
10	7	70
14	8	112
14	8	112
18	10	180
10	11	110
14	11	154
17	11	187
5	12	60
15	12	180
16	12	192
16	12	192
10	14	140
10	14	140
12	14	168
21	14	294
5	15	75
6	15	90
6	15	90
6	15	90
9	15	135
10	15	150
10	15	150
10	15	150
14	15	210
16	15	240
16	15	240
11	16	176
12	16	192
12	16	192
10	17	170
11	17	187
11	17	187
11	17	187
14	17	238
14	17	238
15	17	255
15	17	255
15	17	255
16	17	272
9	18	162
10	18	180
11	18	198
13	18	234
13	18	234
14	18	252
14	18	252

Leaking tanks

SAV	Age	Age*SAV
14	18	252
14	18	252
8	19	152
9	19	171
9	19	171
9	19	171
9	19	171
10	19	190
10	19	190
12	19	228
4	20	80
4	20	80
6	20	120
7	20	140
7	20	140
9	20	180
9	20	180
10	20	200
10	20	200
10	20	200
10	20	200
10	20	200
11	20	220
11	20	220
12	20	240
12	20	240
13	20	260
15	20	300
15	20	300
16	20	320
9	21	189
9	21	189
13	21	273
13	21	273
9	22	198
10	22	220
16	22	352
3	23	69
12	23	276
10	24	240
6	25	150
6	25	150
6	25	150
12	25	300
16	25	400
16	25	400
16	25	400
16	25	400

Leaking tanks

SAV	Age	Age*SAV
16	25	400
9	26	234
9	26	234
16	26	416
12	28	336
10	29	290
5	30	150
8	30	240
10	30	300
14	30	420
3	39	117
9	40	360

TABLE

Soil Aggressiveness Values (SAV) and ages for non-leaking tanks.

SAV	Age	SAV*Age	SAV	Age	SAV*Age	SAV	Age	SAV*Age	SAV	Age	SAV*Age
5	2	10	2	10	20	3	16	48	10	20	200
9	2	18	2	10	20	12	16	192	10	20	200
2	3	6	10	10	100	5	17	85	11	20	220
2	3	6	10	10	100	5	17	85	13	20	260
5	3	15	10	10	100	12	17	204	13	20	260
5	3	15	3	11	33	12	17	204	13	20	260
7	3	21	9	11	99	12	17	204	13	20	260
7	3	21	12	11	132	12	17	204	13	20	260
13	3	39	12	11	132	15	17	255	13	20	260
2	4	8	12	11	132	16	17	272	17	20	340
5	4	20	14	11	154	6	18	108	17	20	340
5	4	20	14	11	154	8	18	144	17	20	340
7	4	28	17	11	187	8	18	144	17	20	340
7	4	28	3	12	36	8	18	144	9	22	198
10	4	40	4	12	48	9	18	162	9	22	198
11	4	44	9	12	108	9	18	162	13	22	286
5	5	25	9	12	108	9	18	162	13	22	286
5	5	25	12	12	144	9	18	162	3	24	72
3	6	18	13	12	156	10	18	180	10	24	240
4	6	24	13	12	156	10	18	180	10	24	240
4	6	24	13	12	156	10	18	180	10	24	240
4	6	24	16	12	192	14	18	252	12	24	288
12	6	72	16	12	192	14	18	252	16	24	384
4	7	28	16	12	192	14	18	252	12	25	300
4	7	28	2	13	26	2	19	38	12	25	300
10	7	70	2	13	26	2	19	38	12	25	300
12	7	84	2	13	26	2	19	38	12	25	300
14	7	98	4	13	52	2	19	38	12	25	300
16	7	112	4	13	52	5	19	95	12	25	300
16	7	112	6	13	78	9	19	171	12	25	300
5	8	40	5	14	70	9	19	171	12	25	300
5	8	40	6	14	84	9	19	171	9	26	234
5	8	40	6	14	84	9	19	171	9	26	234
13	8	104	6	14	84	9	19	171	9	26	234
13	8	104	10	14	140	2	20	40	9	26	234
13	8	104	12	14	168	2	20	40	9	26	234
13	8	104	2	15	30	2	20	40	16	26	416
14	8	112	2	15	30	5	20	100	16	26	416
14	8	112	6	15	90	5	20	100	16	26	416
14	8	112	6	15	90	7	20	140	16	26	416
5	9	45	6	15	90	10	20	200	6	28	168
5	9	45	10	15	150	10	20	200	12	28	336
7	9	63	12	15	180	10	20	200	2	30	60
7	9	63	12	15	180	10	20	200	2	30	60
11	9	99	12	15	180	10	20	200	2	30	60
11	9	99	12	15	180	10	20	200	7	30	210
11	9	99	16	15	240	10	20	200	8	30	240
16	9	144	16	15	240	10	20	200	8	30	240

TABLE 4

Soil Aggressiveness Values (SAV) and ages for non-leaking tanks.

SAV	Age	SAV*Age	SAV	Age	SAV*Age	SAV	Age	SAV*Age	SAV	Age	SAV*Age
5	2	10	2	10	20	3	16	48	10	20	200
9	2	18	2	10	20	12	16	192	10	20	200
2	3	6	10	10	100	5	17	85	11	20	220
2	3	6	10	10	100	5	17	85	13	20	260
5	3	15	10	10	100	12	17	204	13	20	260
5	3	15	3	11	33	12	17	204	13	20	260
7	3	21	9	11	99	12	17	204	13	20	260
7	3	21	12	11	132	12	17	204	13	20	260
13	3	39	12	11	132	15	17	255	13	20	260
2	4	8	12	11	132	16	17	272	17	20	340
5	4	20	14	11	154	6	18	108	17	20	340
5	4	20	14	11	154	8	18	144	17	20	340
7	4	28	17	11	187	8	18	144	17	20	340
7	4	28	3	12	36	8	18	144	9	22	198
10	4	40	4	12	48	9	18	162	9	22	198
11	4	44	9	12	108	9	18	162	13	22	286
5	5	25	9	12	108	9	18	162	13	22	286
5	5	25	12	12	144	9	18	162	3	24	72
3	6	18	13	12	156	10	18	180	10	24	240
4	6	24	13	12	156	10	18	180	10	24	240
4	6	24	13	12	156	10	18	180	10	24	240
4	6	24	16	12	192	14	18	252	12	24	288
12	6	72	16	12	192	14	18	252	16	24	384
4	7	28	16	12	192	14	18	252	12	25	300
4	7	28	2	13	26	2	19	38	12	25	300
10	7	70	2	13	26	2	19	38	12	25	300
12	7	84	2	13	26	2	19	38	12	25	300
14	7	98	4	13	52	2	19	38	12	25	300
16	7	112	4	13	52	5	19	95	12	25	300
16	7	112	6	13	78	9	19	171	12	25	300
5	8	40	5	14	70	9	19	171	12	25	300
5	8	40	6	14	84	9	19	171	9	26	234
5	8	40	6	14	84	9	19	171	9	26	234
13	8	104	6	14	84	9	19	171	9	26	234
13	8	104	10	14	140	2	20	40	9	26	234
13	8	104	12	14	168	2	20	40	9	26	234
13	8	104	2	15	30	2	20	40	16	26	416
14	8	112	2	15	30	5	20	100	16	26	416
14	8	112	6	15	90	5	20	100	16	26	416
14	8	112	6	15	90	7	20	140	16	26	416
5	9	45	6	15	90	10	20	200	6	28	168
5	9	45	10	15	150	10	20	200	12	28	336
7	9	63	12	15	180	10	20	200	2	30	60
7	9	63	12	15	180	10	20	200	2	30	60
11	9	99	12	15	180	10	20	200	2	30	60
11	9	99	12	15	180	10	20	200	7	30	210
11	9	99	16	15	240	10	20	200	8	30	240
16	9	144	16	15	240	10	20	200	8	30	240

FIGURE 3: COMPUTATION OF SAV

		POINTS
I BASIC CHARACTERISTICS		
o Soil Resistivity	<300	12
	300 - 1,000	10
	1,000 - 2,000	8
	2,000 - 5,000	6
	5,000 - 10,000	3
	10,000 - 25,000	1
	>25,000	0
o Soil pH	<3	8
	3 - 5	6
	5 - 6.5	4
	6.5 - 7.5	2
	7.5 - 9	1
	>9	0
o Soil Moisture	Saturated	3
	Damp	2
	Dry	0
II DIFFERENTIAL CHARACTERISTICS		
o Resistivity	>1:10	3
(ratio of extremes)	>1: 5	2
	>1: 3	1
	<1: 3	0
Soil pH	3	2
(Difference in	1.5 - 3	1
pH Value)	0 - 1.5	0
III SULFIDES		
	Positive	4
	Negative	0

corrosivities; that is, a soil with an SAV of 2x is expected to be (on average) twice as corrosive as a soil with an SAV of x.

On first consideration, the Canadian data reveals one important fact: there is a lot of scatter. But it is also clear that non-leaking tanks are clustered somehwat closer to the lower left-hand corner of the diagram than are leaking tanks. Thus, age, SAV, or the combination of the two does appear to have some predictive effect on the probability of leakage.

This tentative conclusion can be verified by simple statistical analyses. Using chi-squared techniques, age, SAV and SAV x age can be tested for statistically significant effects on the probability of leakage. In addition, SAV can be tested to determine if it has any effect independent from the effect of age. The following section will describe each of these analyses.

STATISTICAL TESTS

1. SAV x Age

PACE asserts that the product of SAV and tank age is an appropriate predictor for tank leakage. This assertion makes intuitive sense, for it would appear to allow for the continuing effects of various types of soils. It is also born out by the data, as is indicated by the following contingency table:

TABLE 5

SAV x Age	Number of Leaking Tanks	Number of Non-Leaking Tanks	
0 - 49	0 / 16.92	47 / 30.08	47
50 - 99	11 / 13.68	27 / 24.32	38
100 - 149	10 / 13.32	27 / 23.68	37
150 - 199	36 / 24.12	31 / 42.88	67
200 - 249	22 / 18.00	28 / 32.00	50
250 - 299	14 / 10.08	14 / 17.92	28
300 - 399	8 / 7.92	14 / 14.08	22
≥ 400	7 / 3.96	4 / 7.04	11
	108	192	300

Each cell of this table contains two numbers. The first represents the observed observed number of tanks in each category; these numbers were obtained from Tables 1 and 2. The second number in each cell represents the expected number of tanks falling into that category if SAV x Age had no effect on the probability of leakage. These numbers are computed by multiplying the row total by the column total and dividing by the grand total (300).

One of the assumptions underlying the chi-squared test is that the sampled size is large enough to allow a large-sample approximation. Often, this assumption is expressed as a requirement that there be at least 5 observations in each cell, but more rigorously, the assumption may be stated as a requirement that the expected values be greater than 5 in at least 80% of the sample cells.[5] This assumption is clearly met.

The test statistic (T) is simply the summation of $(x_{ij} - E_{ij})^2/E_i$, over all cells, where x_{ij} is the number of observations in $cell_{ij}$ and E_{ij} is the corresponding expected number of observations. For Table 3, T = 45.11, with (r-1) · (c-1) = 7 degrees of freedom (r and c are the numbers of rows and columns, respectively). This is highly significant, indicating that there is far less than a .1% chance that the difference between the SAV x Age distributions of leaking and non-leaking tanks is random. SAV x Age is therefore a statistically significant factor in the differentiation of leaking and non-leaking tanks. In particular, it appears from Table 5 that SAV x Age has a trichotomous effect. For very low values of SAV x Age, there were no observed leaking tanks (the raw data indicates that for all leaking tanks SAV x Age > 59). For intermediate values (50 < SAV x Age < 150), approximately 28% were leaking, and for high values (SAV x Age > 149), approximately 49% were leaking.

2. Tank Age

The conventional wisdom is that age is a very poor predictor of tank leakage. This, however, is an overstatement, as is evident from the following contingency table:

[5] W. J. Conover, Practical Nonparametric Statistics (John Wiley & Sons: New York), 1971, p. 152.

TABLE 6

Tank Age (yrs)	Number of Leaking Tanks	Number of Non-Leaking Tanks	
0 - 4	0 / 5.76	16 / 10.24	16
5 - 9	5 / 13.32	32 / 23.68	37
10 - 14	12 / 17.28	36 / 30.72	48
15 - 19	41 / 31.32	46 / 55.68	87
20 - 24	30 / 24.12	37 / 42.88	67
25 - 29	14 / 11.88	19 / 21.12	33
> 29	6 / 4.32	6 / 7.68	12
	108	192	300

For this table, T = 28.17, with 6 degrees of freedom. This is significant at something in excess of the 99.9% level. Age therefore is a statistically significant determinant of the probability of leakage. It is clear from Table 1 that while some tanks are leaking at ages 5 to 14, they represent a fairly small fraction (17%) of the entire sample. After age 15, however, the percentage of leakers increases to 46%.

Another interesting observation also emerges from Table 6: if a new contingency table is constructed only for tanks of age 15 or higher, there is no statistically significant effect of age upon the probability of leakage:

TABLE 7

Tank Age	Number of Leaking Tanks	Number of Non-Leaking Tanks	
15 - 19	41 / 39.78	46 / 47.22	87
20 - 24	30 / 30.68	37 / 36.36	67
25 - 29	14 / 15.09	19 / 17.91	33
> 29	6 / 5.49	6 / 6.51	12
	91	108	199

For this table, T = .33, with 3 degrees of freedom. This is not significant, even at the 75% level. Thus, age seems to have an effect only for tanks younger than 15 years; above that age, the probability of leakage is apparently constant.

3. SAV

A contingency table can also be set up to test the effect of SAV upon the probability of leakage:

TABLE 8

SAV	Number of Leaking Tanks	Number of Non-Leaking Tanks	
0 - 4	4 / 13.32	33 / 23.68	37
5 - 9	28 / 31.68	60 / 56.32	88
10 - 14	53 / 47.52	79 / 84.48	132
> 14	23 / 15.48	20 / 27.52	43
	108	192	300

For this table, T = 17.55 with 3 degrees of freedom. This is significant at the 99.9% level.

4. Interaction of SAV and Age

Unfortunately, Age and SAV are not independent variables, as is shown by Table 9:

TABLE 9

Age of Tank	Soil Aggressiveness Value Low (0-6)	Medium (7-12)	High (>12)	
0 - 14 years	37 / 24.91	32 / 47.47	32 / 28.62	101
15 - 20 years	26 / 33.05	72 / 62.98	36 / 37.97	134
> 20 years	11 / 16.03	37 / 30.55	17 / 18.42	65
	74	141	85	300

The T statistic for this table is 17.26 with 4 degrees of freedom. This indicates that there is less than a .5% chance that SAV and Age are uncorrelated. An examination of Table 9 shows that the strongest correlation appears to occur for low and medium SAV's. High-SAV tanks are fairly randomly distributed across all three age groups.

This correlation would be easy to explain if older tanks were more likely common to be found in low-SAV soils; in that case, the relationship between Age and SAV would simply be due to a survival factor (a disproportionate number of older tanks in aggressive soils would already have been replaced long before the survey was taken). Such, however, is not the case. Instead, younger tanks are more likely to be found in low-SAV soils. This cannot be a survival effect. Instead, it probably represents a shift in installation practices in favor of the less corrosive soils.

The correlation between tank age and SAV makes it difficult to determine which is the dominant variable. It is possible, for example, that the observed effects of SAV and SAV x Age are actually the effects of Age, transmitted through the linkages among these variables.

This hypothesis can be tested by constructing contingency tables examining the effects of SAV upon tank leakage for each of the tank age-groups. This will reveal whether SAV has any effect independent from Age.

TABLE 10

Young Tanks
(T = 12.34, 99.5% significance)

	Number of Leaking Tanks	Number of Non-Leaking Tanks	
Low SAV	1 / 6.23	36 / 30.77	37
Medium SAV	5 / 5.39	27 / 26.61	32
High SAV	11 / 5.39	21 / 26.61	32
	17	84	101

Medium-age Tanks
(T = 4.67, 90% significance)

	Number of Leaking Tanks	Number of Non-Leaking Tanks	
Low SAV	7 / 11.84	19 / 14.16	26
Medium SAV	35 / 32.78	37 / 39.22	72
High SAV	19 / 16.39	17 / 19.61	36
	61	73	134

Old Tanks
(T = 2.44, insignificant)

	Number of Leaking Tanks	Number of Non-Leaking Tanks	
Low SAV	6 / 5.08	5 / 5.92	11
Medium SAV	14 / 17.08	23 / 19.92	37
High SAV	10 / 7.85	7 / 9.15	17
	30	35	65

These tables indicate that SAV and Age have some independent effect, but only for the younger tanks. Combining the results of Tables 10 and 7, it appears that neither Age nor SAV have much effect for tanks older than 20 years.

DATA ANALYSIS

Proving that there are statistically significant linkages between leakage rates and SAV, Age, and SAV x Age does not conclude the analysis, however, for it is also necessary to determine the correct interpretation of these linkages. The ultimate goal of such an interpretation is to deduce a cumulative probability distribution for tank failure over a range of SAV x Age categories. Unfortunately, this is not a straightforward task.

One approach to this problem is to assume that the data actually represent the desired cumulative distributions. This assumption would be correct if leaking tanks were never repaired or replaced, for in that case, the number of leaking tanks in any SAV x Age bracket would include both new and pre-existing leaks. Under this simple assumption, the Canadian data yields the following distribution (obtained from the numbers in Table 5):

TABLE 11

SAV x Age	Cumulative Leak Probability (%)
0-49	0
50-99	28.9
100-149	27.0
150-199	53.7
200-249	44.0
250-299	50.0
300-399	36.4
≥ 400	63.6

Since a cumulative probability distribution is by definition non-decreasing, the fluctuation in 300-399 category must be assumed to be anomolous. It can be reduced by combining the two highest brackets:

TABLE 12

SAV x Age	Cumulative Leak Probability %
0-49	0
50-99	28.9
100-149	27.0
150-199	53.7
200-249	44.0
250-299	50.0
≥ 300	45.0

This distribution reveals that tank failure occurs in two spurts: one at SAV x Age between 50 and 99, and the other at SAV x Age between 150 and 199. Other fluctuations in failure rates are statistically insignificant, as can be verified by constructing the appropriate contingency tables.

This distribution has the advantage that it conforms to the expected sigmoidal pattern, with most of the failures occurring during the middle brackets and with some tanks which are effectively immortal even in highly aggressive soils, but the numbers in Table 12 do not seem appropriate. Leakage should not occur at such tightly defined intervals; i.e. there are too few leakers in the 100-149 category. Even more importantly, there are too many immortals. It is very unlikely that half of the tanks would still survive after 40 years in a soil of SAV = 10 (or 20 years with SAV = 20). Yet that is what this distribution seems to indicate.

The problem with the distribution in Table 12 is simple: some leaking tanks will have been replaced relatively soon after they began to leak. Thus, in the upper brackets the survey self-selects for non-leaking tanks (since they are more likely to still be in use), and the cumulative percentages are too low.

One way to cure this problem would be to convert the survey data into a cumulative distribution by computing the number of missing tanks. This could be done by determining the relative numbers of tanks buried in each year and assigning these to SAV brackets according to the distributions in Table 10.[6] To the

[6]This apportionment assumes that the missing tanks in each age group followed the

extent that Table 11 underrepresents certain SAV x Age groups, it can then be assumed that the missing tanks are those which have previously leaked, and the cumulative probabilities can be adjusted accordingly. In order to normalize these calculations, it must be assumed that one SAV x Age-bracket is fully represented. Presumably, this would be bracket 0-49.

Unfortunately, this analysis is fraught with difficulties. Not only are the calculations complex (and somewhat recursive), but the necessary tank burial data is not available. Instead, the best alternative are three data sources on service station construction, and even these are difficult to obtain for Canada (U.S. data are presented in Table 13). Furthermore, once the data are assembled, it appears that the Canadian survey underrepresents younger tanks. This indicates either serious problems in the application of U.S. service station data to Canadian tank burials, or it indicates that the Canadian survey was not random, but instead favored older tanks. In either event, tank attrition cannot be computed, and another approach must be used to obtain a more reasonable cumulative distribution.

A simpler approach to the problem of self-selection of older non-leaking tanks may be found by varying the assumptions underlying Table 12. Instead of assuming that leaks are never detected before the survey, it can be assumed instead that all leaks are detected and the tanks replaced before enough time has passed for the tank to move into the next SAV x Age category. This assumption requires the detection period to be inversely proportional to SAV, but that requirement would be sensible if monitoring is better for tanks known to be in more aggressive soils.

Under this assumption, the failure rates in Table 12 become elements of a probability density function and the corresponding cumulative distribution may be calculated.

---

same SAV distributions as their surviving kin. Such an assumption is probably not accurate, but it is better than nothing.

TABLE 13[1]

Date	Number of Service Stations[2]	Change in Number of Service Stations	API Reports[3] of New Service Stations	API Deactivations[3]	Building[4] Permits	Ratio of Rehabilitations to new Constructions[5]	Number of Rehabilitations[6]
1948	179,647	350					
1949	-	350					
1950	180,347	350					
1951	180,697	350					
1952	181,040	343					
1953	181,390	350					
1954	181,747*	357			9,021	24.30	8664
1955	188,100	6353			9,826	0.55	3473
1956	194,600	6500			10,615	0.63	4115
1957	200,100	5500			5,391	0.00	(109)
1958	206,755	6655			7,801	0.17	1146
1959	207,800	1045			8,050	6.70	7005
1960	208,800	1000					
1961	209,700	900					
1962	210,600	900					
1963	211,473*	873			6,080	5.96	5207
1964	212,600	1127			6,150	4.46	5023
1965	213,550	950			6,500	5.84	5550
1966	214,500	950			6,275	5.60	5325
1967	216,059*	1559			6,606	3.24	5047
1968	219,100	3041	3740	4554	6000-7000	1.14	3500
1969	222,200	3100			6,200	1.00	3100
1970	222,000	(200)	2508	3586			
1971	220,000	(2000)	2068	3630			
1972	226,459*	6459	1689	34[illegible]			

TABLE 13 (Continued)

Date	Number of Service Stations	Change in Number of Service Stations	API Reports of New Service Stations	API Deactivations	Building Permits	Ratio of Rehabilitations to new Constructions	Number of Rehabilitations
1973	215,880	(579)	1172	9342			
1974	196,130	(19,750)	206	6041		9.0	1854
1975	189,480	(6,650)	206	4127		3.8	783
1976	186,340	(3,140)	319	5676		3.03	967
1977	176,400*	(9,940)	284	5683		6.16	1749
1978	172,300	(4,100)	353	5138			
1979	164,790	(7,510)	286	3724		8.34	2385
1980	158,540	(6,250)	169	3380		9.68	1636
1981	151,250	(7,290)	297	4273			
1982	147,000	(4,250)					

1 Source: National Petroleum News, annual Fact Book of petroleum statistics.

2 Obtained by National Petroleum News (NPN) from U.S. government data and NPN estimates. Numbers marked by a star (*) are census totals.

3 Obtained by NPN from American Petroleum Institute totals for a somewhat varying number of responding companies.

4 Obtained by NPN from the Department of Labor, Bureau of Labor Statistics.

5 From 1974 through 1980, these are obtained by NPN from an API survey. For 1954 through 1969, these numbers are obtained from columns 3 and 8.

6 For 1954 through 1969, these numbers are the difference between the number of building permits issued and the change in the total number of service stations. For 1974 through 1980, these numbers are obtained from columns 4 and 7.

TABLE 14

SAV x Age	Probability of New Failure (%)	Cumulative Failure Probability (%)
0-49	0	0
50-99	28.9	28.9
100-149	27.0	46.7
150-199	53.7	75.3
200-249	44.0	86.2
250-299	50.0	93.1
300-399>	36.4	95.6
≥ 400	63.6	98.4

Unfortunately, these cumulative probabilities seem to be too high. Anecdotal data would seem to indicate that a larger percentage of tanks have extremely long lifetimes, even in very aggressive soils. Furthermore, it is likely that some leaks remain undetected over very long periods of time. For both of these reasons, the calculated failure rates are probably too high, though they probably can safely be used as upper bounds on the actual probabilities.[7]

A third assumption may be used in an effort to split the difference between the two polar cases discussed above: it may be assumed that 50% of the leaks detected in each bracket are new, while the remaining leaks are ones that have been continuing since a previous bracket. Under this assumption, the first two brackets are unaltered,[8] but for the other brackets, the previously leaking

---

[7]There is another, more theoretical problem with Table 14: the cumulative probability distribution is highly dependent on the width of the SAV x Age brackets used in its computation. Decreasing their width increases the number of categories (without significantly changing the second column of the table), thereby causing the cumulative probability to converge upon 1.0 at a considerably more rapid rate. Broadening the categories has the reverse effect.

In non-mathematical terms, this problem is related to the detection-period problem discussed earlier. If leaks are detected rapidly, then the data indicates a high rate of new leak formation. If leaks are detected slowly, then the cumulative probability approaches the no-detection assumption depicted in Table 11. Since these problems relate to the proper interpretation of real-world data, they are not the same as the scenarios ultimately to be studied in the computer model. Instead, the goal is to determine just how conservative the Canadian oil companies' detection/repair policies actually were prior to 1977. The use of 50-point brackets seem to be a reasonable assumption for the technology then in use.

[8]The first bracket is unaltered because there are no leaks. The second bracket

tanks must be removed from both the leaking tank category and the bracket totals. With these modifications, the data becomes:

---

is unaltered because to alter it would be contrary to the observation that there are no failures in the first bracket.

TABLE 15

SAV x Age	Number of Leaking Tanks	Number of Previously Non-Leaking Tanks	Percent of New Leaks	Cumulative Leak Probability (%)
0-49	0	47	0	0
50-99	11	38	28.9	28.9
100-149	5	32	15.6	40.0
150-199	18	49	36.7	62.0
200-249	11	39	28.2	72.7
250-299	7	21	33.3	81.8
300-399	4	18	22.2	86.0
≥ 400	3.5	7.5	50.0	93.0

These cumulative probabilities from these three assumptions can be combined in a single table:

TABLE 16

SAV x Age	Lower Bound (Assumption 1)	Upper Bound (Assumption 2)	Assumption 3	Average of Assumption 1-3
0-49	0	0	0	0
50-99	28.9	28.9	28.9	28.9
100-149	27.0	46.7	40.0	37.9
150-199	53.7	75.3	62.0	63.7
200-249	44.0	86.2	72.7	67.6
250-299	50.0	93.1	81.8	75.0
300-399	45.0	95.6	86.0	75.5
≥ 400	45.0	98.4	93.0	78.8

The last column is the one which will be used in the Monte Carlo model, though it is subject to revisions as better data become available.

CAVEATS

The cumulative probability distribution presented in Table 16 must be used with caution, for unfortunately, the Canadian data set does not represent a random survey of existing tanks. Instead, the data were collected in 3 ways:[9]

- Over a 6-month period in 1977, all PACE member companies were requested to report leak incidents. Soil samples were taken at the leaking tanks' sites.
- During this same time period, PACE member companies were requested to report tank decommissionings. Decommissioned tanks were then tested for leaks, and soil samples were taken.
- Other tanks on the same site as a leaking or decommissioned tank were also tested.

Thus, the survey is biased both toward leaking tanks and toward older tanks. (The latter bias occurs because older tanks are more likely to be decommissioned). The age bias is relatively unimportant. The bias toward leaking tanks, however, means that the resulting data present a worst-case portrait of the existing tank situation. This bias may not be overly severe, however, for the fact that only 36% of the sample tanks were leaking indicates that the other two sampling methods may have predominated. Furthermore, this bias may be offset by the fact that the second and third sampling techniques tend to self-select for non-leaking tanks. Nevertheless, an unknown net bias probably results, and the data must be viewed as only an approximation of the results of a truly random survey.

AN ALTERNATIVE APPROACH

Instead of complex calculations based on Age x SAV, it may be more appropriate, given the data biases discussed above, to attempt a simpler model. With this in mind, the data can be grouped into high, middle, and low SAV soils, and failure rate versus age may be calculated for each soil group. The results are presented in Table 17.

---

[9] PACE, "Underground Tank Systems," supra ~~n. 1, p. 48~~, and personal communication with J.R. Clendening, Esso Petroleum. Canada, June 1985.

TABLE 17

Tank Age	Low SAV (≤ 6) Leakers	Low SAV (≤ 6) Non Leakers	Medium SAV (7-12) Leakers	Medium SAV (7-12) Non Leakers	High SAV (≥ 13) Leakers	High SAV (≥ 13) Non Leak
0-4	0	8	0	7	0	1
5-9	0	13	1	8	4	11
10-14	1	15	4	12	7	9
15-19	4	14	22	25	15	7
20-24	4	6	19	18	7	13
≥ 25	5	4	8	17	7	4
	14	60	54	87	40	45

Table 17 may be interpreted under the same 3 assumptions that were used in Tables 11, 12, and 14-16. The resulting probability distributions are presented in Tables 18-20.

The same approach can also be used employing only two SAV categories. If soils are classified as benign when SAV is 9 or less and aggressive when SAV is 10 or greater, then the data can be summarized in Table 21.

Table 21 can be used to calculate cumulative probability distributions as in Tables 18-20. The results, using the same three assumptions, are presented in Tables 22-23.

The 2-part and 3-part SAV distinctions have certain similarities. In both cases, there are clear differences between soils of different aggressivities. These differences can most readily be appreciated by presenting the results in a single table, as is done in Table 24.

These distributions can be plotted graphically, as can the probability of tank failure versus SAV x Age (from Table 16). This is done in Figures 4-9. For interpretive purposes, these graphs have converted the cumulative distributions reported in the tables into the underlying probability densities. Thus, these histograms represent the probability that the tank failure will originate in each of the designated intervals.

These graphs indicate that SAV x Age is probably not the best measure of tank deterioration. The reason for this conclusion is the bimodal nature of the SAV x Age probability density. While such bimodality might possibly be an accurate reflection of the real world, it is more likely that the bimodal distribution results from improperly aggregating unlike distributions. This latter explanation appears particularly appropriate in the present situation. As Figures 4-6 indicate, the probability distributions are differently-shaped for low-SAV and high-SAV soils. Low-SAV soils produce a relatively steady failure rate for all years after year 9, while higher-SAV soils produce much higher failure rates in the lower years, but declining failure rates in later years.[10] Combining these

[10]The reason for the low failure rates after year 19 is simply that by that year, a large fraction of high-SAV tanks have already failed.

TABLE 18. LOW SAV SOILS (SAV ≤ 6)

Cumulative Probability of Leakage (%)

Tank Age	Lower Bound (Detection within 5 years)	Upper Bound (No detection prior to survey)	Assumption 3[1] (75% of survey leaks are new)	Average
0-4	0	0	0	0
5-9	0	0	0	0
10-14	6.3	6.3	6.3	6.3
15-19	22.2	27.1	22.8	24.0
20-24	40.0	56.3	48.5	48.3
≥ 25	55.6	80.6	73.6	69.9

[1] Assumption 3 in this table has been adjusted from that used in Tables 15 and 16 in order to be consistent with the lower leak rates for low-SAV tanks.

TABLE 19. MEDIAN SAV SOILS (7-12)

Cumulative Probability of Leakage (%)

Tank Age	Lower Bound (Detection within 5 years)	Upper Bound (No detection prior to survey)	Assumption 3[1] (50% of survey leaks are new	Average
0-4	0	0	0	0
5-9	11.1	11.1	11.1	11.1
10-14	25.0	33.3	28.9[1]	29.1
15-19	46.8	64.5	50.6	54.0
20-24	51.4	82.8	67.7	67.3
≥ 25	32.0	88.3	73.8	-[2]

[1] This calculation uses a 75% rate of new leak development in order to be consistent with the lower-bound estimates in the previous column.

[2] No number is calculated for this range, for the anomalous decline in probability for the "lower bound" would produce an equally anomalous fluctuation in the average.

TABLE 20. HIGH SAV SOILS (SAV ≥ 13)

Cumulative Probability of Leakage (%)

Tank Age	Lower Bound (Detection within 5 years)	Upper Bound (No detection prior to survey	Assumption 3 (50% of survey leaks are new	Average
0-4	0	0	0	0
5-9	26.7	26.7	26.7	26.7
10-14	43.8	58.8	47.2	49.9
15-19	68.2	86.9	74.5	76.5
20-24	35.0	91.5	79.9	79.9[1]
≥ 25	63.6	96.9	89.3	83.3

[1] Obtained by interpolation between the values for ages 15-19 and ≥ 25. An average of Assumptions 1, 2, and 3 is dominated by the anomalous value for Assumption 1.

TABLE 21

	Benign Soils (SAV ≤ 9)		Aggressive Soils (SAV ≥ 10)	
Age	Number of Leaking Tanks	Number of Non-leaking Tanks	Number of Leaking Tanks	Number of Non-Leaking Tanks
0-4	0	13	0	3
5-9	0	15	5	17
10-14	1	18	11	18
15-19	11	26	30	20
20-24	11	9	19	28
≥ 25	9	12	11	13

TABLE 22. BENIGN SOILS (SAV ≤ 9)

Cumulative Probability of Leakage (%)

Tank Age	Lower Bound (Assuming no detection prior to survey	Upper Bound (Assuming all leaks detected and repaired within 5-year age bracket)	Assumption 3 (67% of observed leaks are new)	Average of Assumptions 1, 2, and 3
0-4	0	0	0	0
5-9	0	0	0	0
10-14	5.3	5.3	5.3	5.3
15-19	29.7	33.4	32.4[1]	31.8
20-24	55.0	70.0	62.8	62.6
≥ 25	42.9	82.9	75.2	67.0

[1] Calculated under the assumption that only one of the observed leakages was pre-existing, in order to be consistent with the preceding bracket's low-leak rate.

TABLE 23. AGGRESSIVE SOILS (SAV ≥ 10)

Cumulative Probability of Leakage (%)

Tank Age	Lower Bound (Assuming no detection prior to survey	Upper Bound (Assuming all leaks repaired within 5-year age bracket)	Assumption 3 (50% of observed leaks are new)	Average
0-4	0	0	0	0
5-9	22.7	22.7	22.7	22.7
10-14	37.9	52.0	48.1[1]	45.0
15-19	60.0	80.8	70.3	70.4
20-24	40.4	88.6	77.8	72.6[2]
≥ 25	45.8	93.8	84.4	74.7

[1] Calculated under the assumption that 80% of the observed leaks are new, in order to be consistent with the previous bracket's observed low leak rate.

[2] Calculated by interpolation between the preceding and following brackets, in order to prevent the decline in the value for assumption 1 from causing anomalous results.

TABLE 24.

Cumulative Probability of Leakage (%)

Tank Age[1]	Low SAV (0 to 6)	Medium SAV (7 to 12)	High SAV (≥ 13)	Benign Soil (0-9)	Aggressive Soil (≥ 10)
4	0	0	0	0	0
9	0	11.1	26.7	0	22.7
14	6.3	29.1	49.9	5.3	45.0
19	24.0	54.0	76.5	31.8	70.4
24	48.3	67.3	79.9	62.6	72.6
≥ 25	69.9	-	83.3	67.0	74.7

[1] Tank ages have been changed from age brackets to the age corresponding to the top of each bracket.

FIGURE 4
LOW SAV SOILS (0-6)

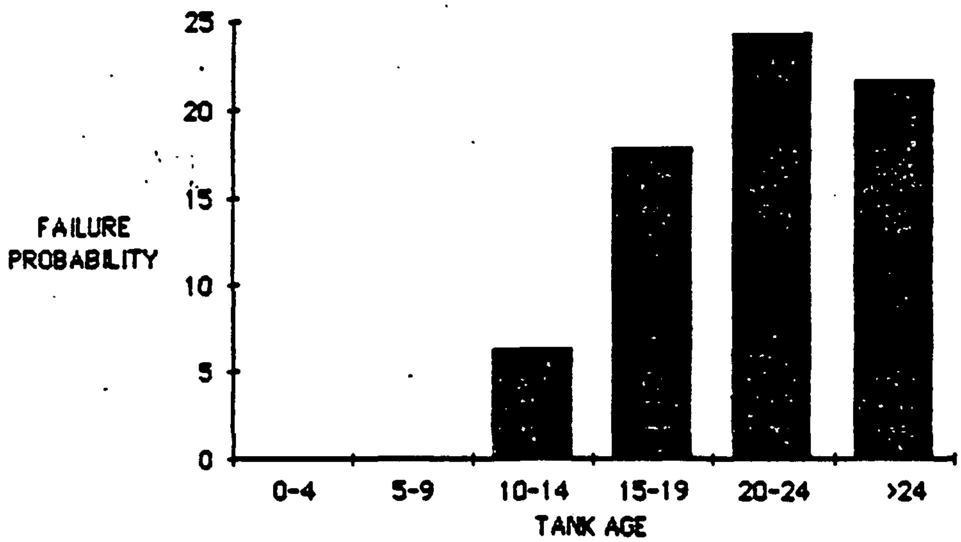


FIGURE 5
MEDIUM SAV SOILS (7-12)

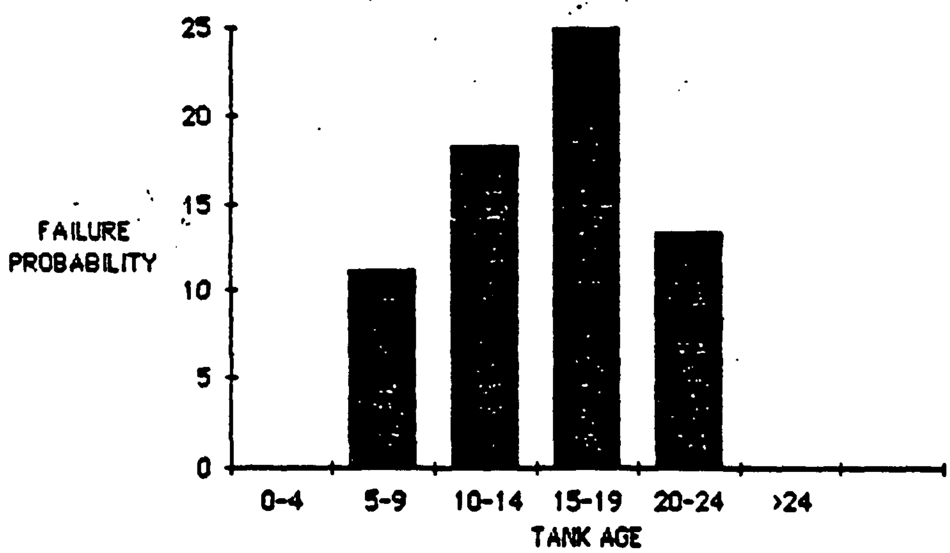


FIGURE 6
HIGH SAV SOILS (13-21)

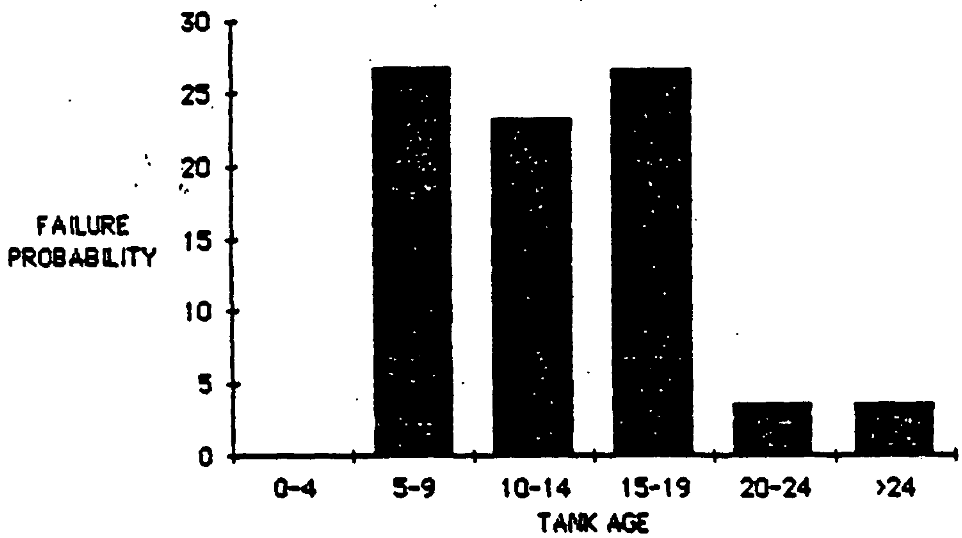


FIGURE 7
BENIGN SOILS (0-9)

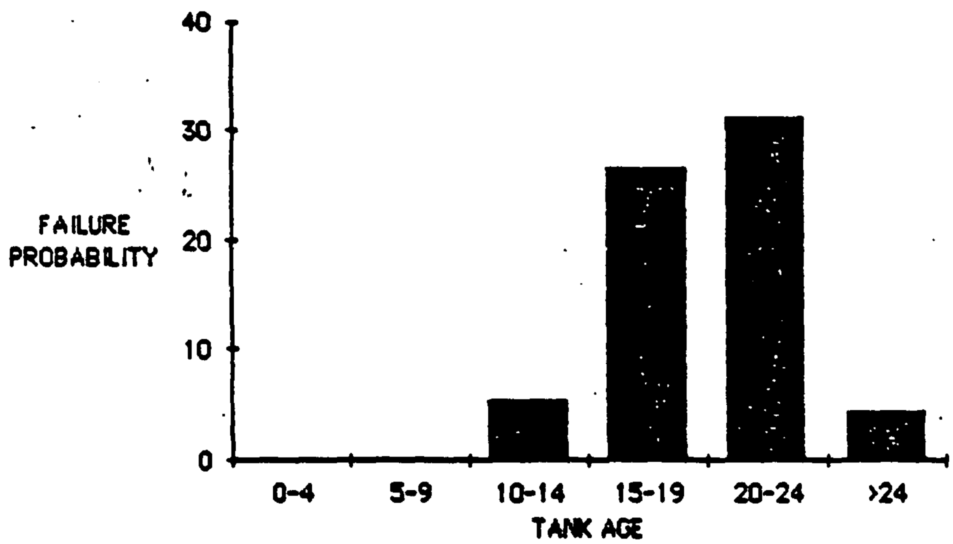


FIGURE 8

AGGRESSIVE SOILS (>10)

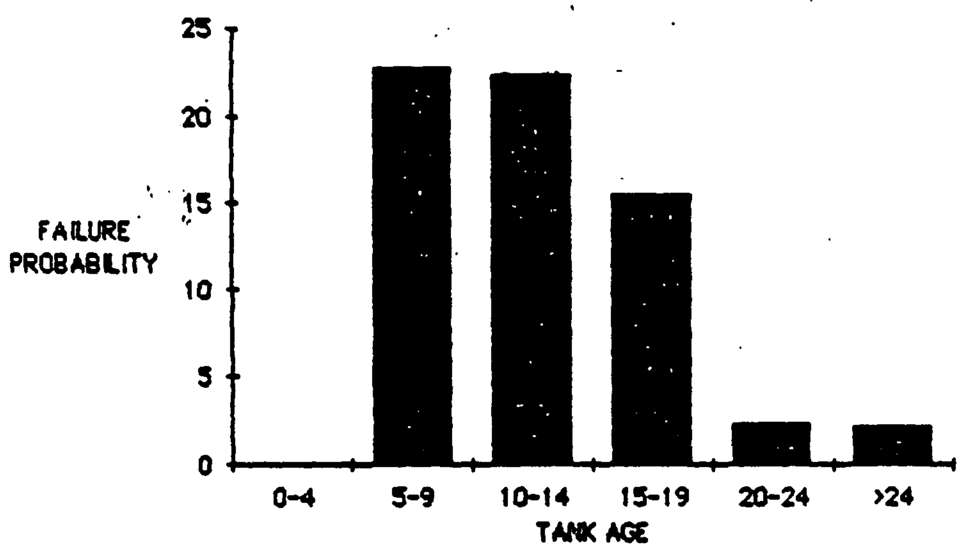
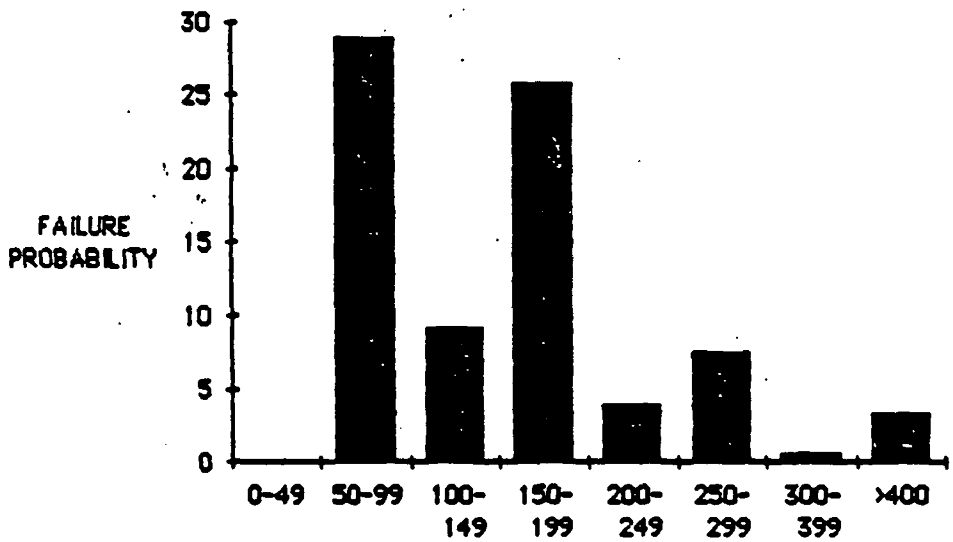


FIGURE 9
FAILURE PROBABILITY USING SAV X AGE



two dissimilar age distributions could easily produce the bimodal distribution depicted in Figure 9, even after the data have been converted from age categories to SAV x Age categories. It therefore appears that the data has greater usefulness if SAV and Age are both used as separated variables than it does if they are combined into the single variable of SAV x Age.

This analysis, however, does not indicate whether two or three SAV categories are preferable. This decision can be facilitated, though, by a re-examination of the raw data in Figures 1 and 2. These scatter diagrams indicate that a substantial percentage of the tanks, particularly leaking ones, are to be found between SAV=9 and SAV=11. There is no theoretical reason for dividing aggressive soils from benign soils at an SAV of either 9, 10, or 11, yet because of the clustering of the data, this arbitrary division can significantly alter the probability density functions when only two SAV categories are used. Thus, the natural clustering of the data favors the use of three SAV categories, and therefore three such categories will be used in the computer model.

COMPUTER MODELING

In order to carry out the Monte Carlo simulation on a year-by-year basis, it is necessary to calculate failure probabilities for each year between 1 and 20. This can most conveniently be done by straight-line interpolation between the age brackets used in Table 24. The results are presented in Tables 25 and 26. (Table 25 presents cumulative probabilities, while Table 26 presents probability densities). Once SAV is determined, these tables can then be used to determine annual probabilities of failure.

SAV can be determined in one of two ways: it can either be postulated as an exogenous parameter, or it can be determined stochastically. The deterministic approach is the simplest, and is to be preferred for the initial simulations, but the stochastic approach may be useful for modeling more complex scenarios.

The PACE data can be used to obtain a distribution of SAV's for the 300 tanks covered by the survey. This distribution is presented in Table 27.

While there is no guarantee that this distribution is representative of U.S. soils, it is probably a reasonable approximation, and it can be used to calcu-

TABLE 25. CUMULATIVE PROBABILITIES OF FAILURE IN LOW-, MEDIUM-, AND HIGH-SAV SOILS

Tank Age	Cumulative Failure Probability (%) Low SAV (0-6)	Medium SAV (7-12)	High SAV (≥ 13)
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	0	2.22	5.34
6	0	4.44	10.68
7	0	6.66	16.02
8	0	8.88	21.36
9	0	11.10	26.70
10	1.26	14.70	31.34
11	2.52	18.30	35.98
12	3.78	21.90	40.62
13	5.04	25.50	45.26
14	6.30	29.10	49.90
15	9.84	34.08	55.22
16	13.38	39.06	60.54
17	16.92	44.04	65.86
18	20.46	49.02	71.18
19	24.00	54.00	76.50
20	28.86	56.66	77.18

TABLE 26. PROBABILITY DENSITIES FOR FAILURE IN LOW-, MEDIUM-, AND HIGH-SAV SOILS

Tank Age	Probability Density (%) Low SAV (0-6)	Medium SAV (7-12)	High SAV (> 13)
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	0	2.22	5.34
6	0	2.22	5.34
7	0	2.22	5.34
8	0	2.22	5.34
9	0	2.22	5.34
10	1.26	3.60	4.64
11	1.26	3.60	4.64
12	1.26	3.60	4.64
13	1.26	3.60	4.64
14	1.26	3.60	4.64
15	3.54	4.98	5.32
16	3.54	4.98	5.32
17	3.54	4.98	5.32
18	3.54	4.98	5.32
19	3.54	4.98	5.32
20	4.86	2.66	0.68

TABLE 27. DISTRIBUTION OF SOIL AGGRESSIVENESS VALUES

SAV	Number of Tanks	Probability Density	Cumulative Probability (%)
1	0	0	0
2	20	6.7	6.7
3	7	2.3	9.0
4	10	3.3	12.3
5	21	7.0	19.3
6	16	5.3	24.7
7	10	3.3	28.0
8	7	2.3	30.3
9	34	11.3	41.7
10	43	14.3	56.0
11	12	4.0	60.0
12	35	11.7	71.7
13	22	7.3	79.0
14	20	6.7	85.7
15	7	2.3	88.0
16	28	9.3	97.3
17	6	2.0	99.3
18	1	.3	99.7
19	0	0	99.7
20	0	0	99.7
21	1	.3	100.0

TABLE 28. CONDITIONAL SAV DISTRIBUTION UNDER A REQUIREMENT THAT SAV NOT EXCEED 10

SAV	Probability Density (%)	Cumulative Probability (%)
1	0	0
2	11.9	11.9
3	4.2	16.1
4	5.9	22.0
5	12.5	34.5
6	9.5	44.0
7	5.9	50.0
8	4.2	54.1
9	20.2	74.4
10	25.6	100.0

late the probability that any given tank falls into each of the three SAV categories used in Tables 25 and 26. In addition, the SAV distribution can be used to obtain the conditional SAV-distribution under various regulatory scenarios. Consider, for example, a regulation requiring that SAV not exceed 10. If this regulation has no effect on the distribution of acceptable SAV's, then the conditional SAV distribution can be obtained simply by dividing the numbers in Table 27 by 56% (the unconditional probability that SAV $\leq$ 10). The results are presented in Table 28.

Similar computations could be undertaken for any other SAV cut-off. These results could then be used to determine the probability that the tank falls in each of the three SAV-categories used to predict the probability of failure.

More complex regulatory scenarios could also be modeled under this approach. For example, a proposed regulation might make the use of cathodic protection or secondary containment dependent on the aggressiveness of the soil in question. This could be modeled by first sampling a value for SAV and then using that value to determine other system parameters. Such a scenario is considerably more complicated than the scenarios that have been modeled to date, but if it is desired that such composite scenarios be studied, they are well within the capabilities of the model.

APPENDIX C

TANK FAILURE CASE STUDIES

TANK FAILURE CASE STUDY #1

SITE: Transformer manufacturing plant of Federal Pioneer Ltd

LOCATION: Regina, Saskatchewan, Canada

RELEASE MECHANISM: Pipe rupture

DATA SOURCE

- "A Case Study of a Spill of Industrial Chemicals: Polychlorinated Biphenyls and Chlorinated Benzenes," National Research Council Canada, NRCC No. 17586, 1980.

DESCRIPTION OF RELEASE

- In mid-1976 an underground pipe carrying PCB's from a 31,000 liter tank ruptured.

CAUSE OF RELEASE: Underground pipe ruptured

RELEASE MATERIALS

- How Detected:
- Material Types: PCB's (70%), chlorobenzenes (30%)
- Quantities Released: 6800 - 21,000 liters

RELEASE DURATION

RELEASE ENVIRONMENT

- Land, Water, Air, Unknown: land
- Description of contamination: underground

COMMENTS

- Additional information on this site can be found in:

  - Roberts, Russell J., John A. Cherry, Franklin W. Schwartz, "A Case Study of a Chemical Spill: Polychlorinated Biphenyl, (PCB's)--1. History, Distribution, and Surface Translocation," in Water Resources Research, Vol. 18, No. 3, pp. 525-534, June 1982.

- Roberts, Russell J., John A. Cherry, Franklin W. Schwartz, "A Case Study of a Chemical Spill: Polychlorinated Biphenyls (PCB's)--2. Hydrological Conditions and Containment Migration," in Water Resource Research, Vol. 18, No. 3, pp. 535-545, June 1982.

TANK FAILURE CASE STUDY #2

SITE: Unknown

LOCATION: Unknown

RELEASE MECHANISM: Catastrohic release

DATA SOURCE

- Dartnell Jr., R.C., T.A. Ventrone, "Explosion of a Para-Nitro-Meta-Cresol Unit," Chemical Engineering Progress, Vol. 67, No. 6, pp. 58-61.

DESCRIPTION OF RELEASE

- A temperature indicator on the feed-tank indicated a temperature of 154° C for the entire holding period up to the time of explosion. This was also the temperature of the product leaving the process step immediately upstream. Prior to the explosion, the pressure on the feed tank increased from 40 to 100%. No product was being fed.

CAUSE OF RELEASE: Explosion

RELEASE MATERIALS

- How Detected: pressure sensor
- Material Types: para-nitro-meta-cresol (PNMC)
- Quantities Released: 1500 gallons

RELEASE DURATION

TANK DESIGN AND OPERATING CHARACTERISTICS

- Tank Use: storage
- Equipment Material: stainless steel

TANK FAILURE CASE STUDY #3

SITE: Unknown

LOCATION: Unknown

RELEASE MECHANISM: Unknown, probably tank corrosion

DATA SOURCE

- Eagen Jr., H.B., et al. "Removal of Hazardous Fluid from the Groundwater in a Congested Area--A Case History," Control of Hazardous Material Spills, Proceedings of 1976 National Conference on Controls of Hazardous Material Spills.

DESCRIPTION OF RELEASE

- Hydrocarbon migrated through the top of a shallow water table. It seeped at the land surface in low lying areas discharging 200 gallons per day into a perennial stream. Domestic wells were abandoned and product seeped into sewer lines.

CAUSE OF RELEASE: Unknown

RELEASE MATERIALS

- How Detected:
- Material Types: Hydrocarbon product (80% gasoline)
- Quantities Released: 500,000 gallons

RELEASE DURATION "long period of time"

RELEASE ENVIRONMENT

- Land, Water, Air, Unknown: water
- Description of contamination: underground into groundwater and from groundwater into surface water

COMMENTS

- This paper deals mostly with recovery operations and doesn't describe the failure event very well.

TANK FAILURE CASE STUDY #5

SITE: Bulk Terminals, tank storage farm

LOCATION Calumet Harbor Area, Chicago, Illinois

RELEASE MECHANISM: Pipe rupture

DATA SOURCE

- Hampson, T.R. "Chemical Leak at a Bulk Terminals Tank Farm," Control of Hazardous Material Spills, Proceedings of 1976 National Conference on Control of Hazardous Material Spills

DESCRIPTION OF RELEASE

- Silicon tetrachloride leaked from a pipe rupture, forming an acid cloud with the moist air. A rain storm worsened the situation, causing such dense fumes that electrical lines and transformers corroded and failed.

CAUSE OF RELEASE

- A block valve on an inlet line and a pressure relief valve were inadvertently closed. Pressure in the line began to build up. At about 12:30 p.m. on April 26, 1974, a flexible coupling on the inlet line burst under the pressure. The entire piping system shifted and a second line also cracked.

RELEASE MATERIALS

- How Detected: fumes
- Material Types: silicon tetrachloride
- Quantities Released: plume contained 40 ppm of HCl; 284,000 gallons were leaked; initially the acid cloud was about .25 miles wide, 1000 to 1500 feet high, and 1 mile in length, but due to the storm, it grew to 9 miles in length.

RELEASE DURATION

- It was 2.5 to 3 days before leak was sealed. However, 7 days passed before there was no threat of additional releases.

TANK DESIGN AND OPERATING CHARACTERISTICS

- Tank Use: storage, steel tank with dry air or nitrogen padding equipment, capacity of 1,500,000 gallons. The tank contained 750,000 gallons of fluid.
- Tank/Treatment Components, Ancillary Equipment: extra automatic pressure vents, special valves, and closed transfer pumps.
- Equipment That Failed: flexible coupling, piping system, tank
- Dikes/Berms: present, they contained the liquid spill.

RELEASE ENVIRONMENT

- Land, Water, Air, Unknown: air and land
- Description of contamination: silicon tetrachloride poured out of tank into diked area and reacted vigorously with water in the air and rainfall to form HCl vapor. The enormous acid cloud spread over the far south side of the city.

COMMENTS

- Additional information on this site is located under:

  - Hoyle, W.C. and Melvin, G.L. "A Toxic Substance Leak in Retrospect: Prevention and Response." Control of Hazardous Material Spills, Proceedings of 1976 National Conference on Control of Hazardous Material Spills.

TANK FAILURE CASE STUDY #6

SITE: Service station

LOCATION: Cresskill, New Jersey

RELEASE MECHANISM: Tank corrosion

DATE SOURCE

- Kramer, William H. "Ground-water Pollution from Gasoline," GWMR, Spring 1982, pp. 18-22.

CAUSE OF RELEASE: Leaks in four 4000-gallon steel tanks due to corrosion.

RELEASE MATERIALS

- How Detected: routine inventory check
- Material Types: gasoline
- Quantities Released: 1200 gallons

RELEASE DURATION two or three days

TANK DESIGN AND OPERATING CHARACTERISTICS

- Tank Use: gasoline storage for service station
- Equipment That Failed: tank
- Equipment Material: steel
- Equipment Age: 17 years

RELEASE ENVIRONMENT

- Land, Water, Air, Unknown: land
- Description of contamination: Underground

COMMENTS

- The article is very detailed; it indicates how the gasoline was recovered and the cost of recovery.

TANK FAILURE CASE STUDY #7

SITE: Unknown

LOCATION: Unknown

RELEASE MECHANISM: Interior tank corrosion

DATA SOURCE

- Bosich, Joseph F. Corrosion Prevention for Practicing Engineers, Barnes and Noble, Inc. New York, 1970, p. 186.

DESCRIPTION OF RELEASE

CAUSE OF RELEASE

- A workman accidentally dropped a 1" diameter hexagon-shaped nut to the bottom of the tank, causing localized interior corrosion.

RELEASE MATERIALS

- How Detected: visual detection
- Material Types: concentrated sulfuric acid
- Quantities Released: Unknown

RELEASE DURATION

TANK DESIGN AND OPERATING CHARACTERISTICS

- Tank Use: storage
- Equipment Material: steel

TANK FAILURE CASE STUDY #8

SITE: Unknown

LOCATION: Sussex, Wisconsin

RELEASE MECHANISM: Unknown, probably tank corrosion

DATA SOURCE

- Lindoff, David E., Keros Cartwright, Groundwater Contamination: Problems and Remedial Actions, Environmental Geology Notes, Illinois State Geological Survey, May 1977, No. 81, Case history 88, p. 50.

DESCRIPTION OF RELEASE

CAUSE OF RELEASE

RELEASE MATERIALS

- How Detected: complaints that water from some wells tasted and smelled like petroleum
- Material Types: petroleum products
- Quantities Released:

RELEASE DURATION

TANK DESIGN AND OPERATING CHARACTERISTICS

- Tank Use: storage

RELEASE ENVIRONMENT

- Description of contamination: surficial material, surface water, and probably groundwater

TANK FAILURE CASE STUDY #9

SITE: Unknown

LOCATION: Spring Mills, Pennsylvania

RELEASE MECHANISM: Unknown, probably corrosion or rupture

DATA SOURCE

- Lindoff, David E., Keros Cartwright, Ground-Water Contamination: Problems and Remedial Actions, Environmental Geology Notes, Illinois State Geological Survey, May 1977, No. 81, Case History 24, p. 30.

DESCRIPTION OF RELEASE

CAUSE OF RELEASE: Storage tank leak

RELEASE MATERIALS

- How Detected: explosion
- Material Types: gasoline
- Quantities Released: 200-250 gallons

RELEASE DURATION: 2 weeks

TANK DESIGN AND OPERATING CHARACTERISTICS

- Tank Use: storage

RELEASE ENVIRONMENT

- Land, Water, Air, Unknown: water
- Description of contamination: groundwater

TANK FAILURE CASE STUDY #10

SITE: Unknown

LOCATION: Southeastern Pennsylvania

RELEASE MECHANISM: Unknown, probably tank corrosion

DATA SOURCE

- Lindoff, David E., Keros Cartwright, Ground-Water Contamination: Probems and Remedial Actions, Environmental Geology Notes, Illinois State Geology Survey, May 1977, No. 81, p. 35, Case History 19.

DESCRIPTION OF RELEASE

CAUSE OF RELEASE: Leak in buried 10,000-gallon tank

RELEASE MATERIALS

- How Detected: appeared in a stream
- Material Types: fuel oil
- Quantities Released: 60,000 gallons

RELEASE DURATION

TANK DESIGN AND OPERATING CHARACTERISTICS

- Tank Use: storage

RELEASE ENVIRONMENT

- Land, Water, Air, Unknown: water
- Description of contamination: surface and groundwater

TANK FAILURE CASE STUDY #11

SITE: Unknown

LOCATION: Unknown

RELEASE MECHANISM: Unknown, probably tank corrosion or rupture

DATA SOURCE

- Lindorff, David E., Cartwright, Keros; Ground-Water Contamination: Problems and Remedial Actions, Illinois State Geological Survey Environmental Geology Notes, May 1977, No. 81, case history 5, p. 32.

DESCRIPTION OF RELEASE

- A leak was discovered in a gasoline storage tank at a service stastion. Further investigation indicated that several thousand gallons of gasoline had been lost over a period of three weeks.

CAUSE OF RELEASE: Leak in storage tank

RELEASE MATERIALS

- How Detected: fumes in nearby houses
- Material Types: gasolines
- Quantities Released: several thousand gallons

RELEASE DURATION 3 weeks

TANK DESIGN AND OPERATING CHARACTERISTICS

- Tank Use: storage

RELEASE ENVIRONMENT

- Land, Water, Air, Unknown: groundwater, explosive concentrations of fumes in four houses
- Description of contamination:

TANK FAILURE CASE STUDY #12

SITE: Essex Industrial Chemicals, Inc. chemical processing plant

LOCATION: Baltimore, Maryland

RELEASE MECHANISM: Tank rupture

DATA SOURCE

- "News in Brief: Hazardous Materials," Hazardous Materials Intelligence Report, 30 December, 1983, pp. 3-4.

DESCRIPTION OF RELEASE: An outdoor storage tank burst

CAUSE OF RELEASE

RELEASE MATERIALS

- How Detected: storage tank burst
- Material Types: sulfuric acid
- Quantities Released: 485,000 gallons

RELEASE DURATION

TANK DESIGN AND OPERATING CHARACTERISTICS

- Tank Use: storage

RELEASE ENVIRONMENT

- Land, Water, Air, Unknown:
- Description of contamination: approximately 388,000 gallons traveled over the frozen ground at the plant and spilled into the Cabin Branch waterway, which leads into Curtis Creek and eventually into the Chesapeake Bay.

TANK FAILURE CASE STUDY #13

SITE: Allied Chemical Corporation

LOCATION: Louisiana

RELEASE MECHANISM: Tank rupture

DATA SOURCE

- Shields, Edward, Dessert, W.J., "Learning a Lesson from a Sulfuric Acid Tank Failure," Pollution Engineering, December 1981, pp. 39-40.

DESCRIPTION OF RELEASE: Into the ground

CAUSE OF RELEASE

- An inlet nozzle for the addition of acid to the tank was located too close to the tank wall. The cast iron inlet pipe broke due to corrosion and the high velocity of the incoming acid stripped the protective coating on the sides of the tank. Eventually the tank ruptured.

RELEASE MATERIALS

- How Detected: rupture in tank
- Material Types: 93% sulfuric acid
- Quantities Released: 2500 tons

RELEASE DURATION: 625 minutes (10.4 hours)

TANK DESIGN AND OPERATING CHARACTERISTICS

- Tank Use: storage
- Tank/Treatment Components, Ancillary Equipment: outlet fittings, inlet nozzle manhole
- Equipment That Failed: vertical weld
- Equipment Material: A-283 grade C steel plate
- Equipment Age: Unknown
- Corrosion Protection: ferrous sulfate film

RELEASE ENVIRONMENT

- Land, Water, Air, Unknown:
- Description of contamination: effluent discharge pumps to Mississippi River were turned off and the rain water drainage pipe from the tank farm impoundment area was sealed.

COMMENTS

- A 3000-ton sulfric acid tank in southern Canada also failed because the inlet nozzle was too close to the tank wall.

TANK FAILURE CASE STUDY #14

SITE: Unknown

LOCATION: Unknown

RELEASE MECHANISM: Pipe rupture

DATA SOURCE

- Vervalin, Charles H., "Learn from HPI plant fires," Hydrocarbon Processing

DESCRIPTION OF RELEASE

- About 1000 gallons of the hydrocarbon mixture flowed through a 3/8" pipe opening in the pump housing from which the pipe plug had fallen. Most was absorbed by the ground, however some flowed about 50 feet from the tank through a shallow ditch.

CAUSE OF RELEASE

- A pipe plug had fallen or had been blown. The plug was non-metallic.

RELEASE MATERIALS

- How Detected: fire
- Material Types: hydrocarbon mixture of cyclohexane and n-heptane
- Quantities Released: 1000 gallons

RELEASE DURATION

TANK DESIGN AND OPERATING CHARACTERISTICS

- Tank Use: storage

RELEASE ENVIRONMENT

- Land, Water, Air, Unknown: land
- Description of contamination: The leaking fluid was absorbed by the ground. Some of it flowed about 50 feet from the tank to a shallow ditch.

TANK FAILURE CASE STUDY #15

SITE: Tank farm of General American Transportation Co.

LOCATION: San Pedro, California

RELEASE MECHANISM: Pipe rupture

DATA SOURCE

- Vervalin, Charles H., "Learn from HPI Plant Fires," Hydrocarbon Processing, December 1972, pp. 49-50.

DESCRIPTION OF RELEASE

- A tank truck collided with a pipe, and fire engulfed the tank and truck. The fire spread to nearby trucks.

CAUSE OF RELEASE

- A tank truck apparently sheared a pipe leading to a 30,000 gallon tank.

RELEASE MATERIALS

- How Detected: fire
- Material Types: vinyl acetate
- Quantities Released: 30,000 gallons

RELEASE DURATION

TANK DESIGN AND OPERATING CHARACTERISTICS

- Tank Use: storage
- Equipment That Failed: pipe
- Dikes/Berms: diked area around tank farm

RELEASE ENVIRONMENT

- Land, Water, Air, Unknown: land
- Description of contamination:

TANK FAILURE CASE STUDY #16

SITE: Oil processing and reclamation facility, Bridgeport Rental and Oil Services

LOCATION: Southern New Jersey

RELEASE MECHANISM: Tank corrosion

DATA SOURCE

- Whittaker, Kenneth T., Goltz, Robert, "Cost Effective Management of an Abandoned Hazardous Waste Site by a Staged Clean-up Approach," Management of Uncontrolled Hazardous Waste Sites, 1982, pp. 262.

DESCRIPTION OF RELEASE

CAUSE OF RELEASE: Tank corrosion

RELEASE MATERIALS

- How Detected:
- Material Types: uncharacterized hydrocarbons, various benzene and phenolic polyaromatic hydrocarbons (phenanthene, napthalene) lagoon surface -- high concentration of solvents and PCBs
- Quantities Released: 5 of the 88 on-site 300,000-gallon tanks were empty

RELEASE DURATION

TANK DESIGN AND OPERATING CHARACTERISTICS

- Tank Use: storage

RELEASE ENVIRONMENT

- Land, Water, Air, Unknown: water (surface and groundwater)
- Description of contamination:

TANK FAILURE CASE STUDY #17

SITE: An electronic components manufacturing plant

LOCATION: A suburban area adjacent to a major city. The site is surrounded by residential neighborhoods and small farms.

RELEASE MECHANISM: Unknown, presumably tank corrosion

DATA SOURCE

- Assessment of the Technical, Environmental and Safety Aspects of Storage of Hazardous Waste in Underground Tanks, Vol. I, SCS Engineers, Reston, Virginia, August 1983, pp. 3-36 - 3-46.

DESCRIPTION OF RELEASE

- Lack of inventory and/or environmental monitoring, tank inspection, or tank testing programs at this site allowed a waste solvent storage tank leak to go undetected for approximately 1½ years. The leak material contaminated soil and ground water. As a result of the duration and size of the leak and the hydrogeology of the site, transport of the contamination into three aquifers and over an area of about 1/3 square mile occurred.

CAUSE OF RELEASE

RELEASE MATERIALS

- How Detected: a mass balance analysis on the solvents entering and exiting the plant disclosed a leaking tank
- Material Types: solvents - Acetone, 1-1-Dichloroethylene, Freon 113, Isopropyl alcohol, 1.1.1-Trichloroethane, and Xylene
- Quantities Released: 58,000 gallons

RELEASE DURATION 1½ years

TANK DESIGN AND OPERATING CHARACTERISTICS

- Tank Use: storage

RELEASE ENVIRONMENT

- Land, Water, Air, Unknown: land
- Description of contamination:

TANK FAILURE CASE STUDY #18

SITE: A manufacturing plant that produces electronic computing equipment, semi-conductors and related devices.

LOCATION: A suburban area adjacent to a major city and is surrounded by residential neighborhoods, small farms, a hospital, and a golf course.

RELEASE MECHANISM: Unknown, but includes a corroded pipe

DATA SOURCE

- Assessment of the Technical, Environmental and Safety Aspects of Storage of Hazardous Waste in Underground Tanks, Vol. I, SCS Engineers, Reston, Virginia, August 1983, pp. 3-47 - 3-64.

DESCRIPTION OF RELEASE

CAUSE OF RELEASE

- Some of the probable causes are improper disposal of the chemicals, past operational problems, and a corroded drainline, but most of the causes are unknown.

RELEASE MATERIALS

- How Detected: unknown
- Material Types: solvent (acetone; ethyl amyl ketone; Freon 113; isopropyl alcohol; 1,1,1-trichloroethane; 1,1,1-trichloroethylene; or Xylene)
- Quantities Released:

RELEASE DURATION

TANK DESIGN AND OPERATING CHARACTERISTICS

- Tank Use: storage, treatment, sumps
- Equipment Material: concrete, fiberglass, carbon steel, stainless steel

RELEASE ENVIRONMENT

- Land, Water, Air, Unknown: land
- Description of contamination:

COMMENTS

- Lack of inventory and/or environmental monitoring, tank inspection or tank testing programs at this site allowed many leaks to go undetected for as long as 11 years before detection. The source of pollution has been determined for only one of the three areas found to have soil and groundwater contamination. Transport of the released chemicals into three aquifers for over a mile away from the site resulted from the duration and size of the leaks and the hydrogeology of the area.

- This appears to be the same site as the one discussed in the preceding case study, but this incident apparently involves a separate set of failures.

TANK FAILURE CASE STUDY #19

SITE: Agricultural chemical manufacturing plant

LOCATION: Northern California

DATE SOURCE

- United States Environmental Protection Agency, Case Studies 1-23: Remedial Response at Hazardous Waste Sites, EPA-540/2-84-0026, March 1984 (Case Study #2).

RELEASE MECHANISM

- Pipe corrosion or rupture, accidental pills, and tank corrosion or rupture.

DESCRIPTION OF RELEASE

- The tanks in question were part of the treatment system for rainfall run-off and rinsewater from the plant's chemical handling areas. 15,000 gallons leaked from an underground "skimmer tank." There were also a number of small-scale chemical spills, and leakage from 2 joints in a 300' chemical drain used to connect parts of the system.

CAUSES OF RELEASE: Unknown, but probably include corrosion or rupture of both the tank and the drain.

RELEASE MATERIALS

- How Detected: "Foul taste" in nearby drinking wells.
- Material Types: Toluene and various herbicides.
- Quantities Released: In excess of 15,000 gallons.

RELEASE DURATION

- Unknown. The system was constructed in 1971; the leak was discovered in 1979.

RELEASE ENVIRONMENT

- Land, Water, Air, Unknown: land
- Description of contamination: There was contamination of shallow groundwater. Nearby drinking wells had a "foul taste," but no detectable chemicals.

TANK FAILURE CASE STUDY #20

SITE: Biocraft Laboratories

LOCATION: Waldwick, NJ

RELEASE MECHANISM: Gasket leak

DATA SOURCE:

- United States Environmental Protection Agency, Case Studies 1-23: Remedial Response at Hazardous Waste Sites, EPA-540/2-84-0026, March 1984 (Case Study #4).

DESCRIPTION OF RELEASE

- A gasket in a fill pipe for an underground storage tank disintegrated due to incompatibility with the waste.

CAUSE OF RELEASE

- Incompatibility between gasket and waste

RELEASE MATERIALS

- How Detected: Groundwater testing
- Material Types: Methylene chloride, N-butyl alcohol, dimethyl aniline, acetone, and a variety of trace organics.
- Quantities released: Uncertain--possibly as much as 360,000 lbs.

RELEASE DURATION: Probably 3 years

TANK DESIGN AND OPERATING CHARACTERISTICS

- Tank use: storage
- Equipment that failed: gasket
- Tank design: steel tank with no secondary containment and apparently no corrosion protection
- Age of system: new (constructed in 1972, failure detected in 1975)

RELEASE ENVIRONMENT:

- Land, Water, Air, Unknown: land
- Extent of contamination: Groundwater was contaminated. The release was also the probable cause of a fish kill in a nearby stream in 1973.

TANK FAILURE CASE STUDY #21

SITE: General Electric transformer manufacturing and repair facility

LOCATION: Oakland, CA

RELEASE MECHANISM: Accidental spills, overflows, and tank rupture

DATA SOURCE:

- United States Environmental Protection Agency, Case Studies 1-23: Remedial Response at Hazardous Waste Sites, EPA-540/,2-84-0026, March 1984 (Case Study #9).

DESCRIPTION OF RELEASE

- Over the operating history of the plant, a number of spills had occurred (a) at an above-ground tank farm used for a petroleum-based thinner and oil; (b) near two above-ground 5,000-gallon tanks used for Pyranol (contains PCB); (c) in the area where rail tank cars were unloaded by pumping; (d) possibly due to minor leakage from oil-warming operations inside the building; and (e) from a mobile filtering unit that would occasionally "blow" from too much pressure.

  Additional contamination came from trench burial of liquid PCB's and contaminated solids such as dialectric paper, and from continued discharges from a lab sink following the collapse of a septic tank (date of collapse is unknown. Discharges continued until the mid 1960's).

CAUSES OF RELEASE

- Above-ground spills
- Overflows
- Tank rupture

RELEASE MATERIALS

- How detected:
- Material types: Hydrocarbon products and PCB-contaminated oils
- Quantities released: 20,000 gallons
-

RELEASE DURATION: Miscellaneous spills between 1927 and 1975.

RELEASE ENVIRONMENT

- Land, Water, Air, Unknown: land
- Description of contamination: surface spills and underground leaks. There was widespread contamination of on-site soils and groundwater.

TANK FAILURE CASE STUDY #22

SITE: Houston Chemical Company

LOCATION: Houston, MO.

RELEASE MECHANISM: Tank rupture and pipe design error

DATE SOURCE

- United States Environmental Protection Agency, Case Studies 1-23: Remedial Response at Hazardous Waste Sites, EPA-540/2-84-0026, March 1984 (Case Study #13).

DESCRIPTION OF RELEASE

- The tank was a 21,000-gallon, steel, horizontal, above-ground storage tank. There was no containment system. It collapsed for several reasons:

  - The saddle support blocks were not sufficient either in spacing or number.

  - There were weaknesses due to corrosion and previous abuse.

  - The saddle support blocks were not engineered to fit the curvature of the tank.

  - A drain pipe and valve were installed on the underside of tank. When the tank collapsed, the drain control valve and piping sheared off. This was a design error.

  An overflow pit contained 5% of the spill. The remainder bypassed the pit due to the absence of suitable dikes. The oil flowed into a roadside ditch, under a culvert and into a catch basin where it remained temporarily. It then infiltrated the ground, reappearing 125' downgradient. Eventually it flowed into a farm pond where the water level was low enough that it remained.

  The initial report was not received by EPA until 4 days after the spill. That report falsely stated that the spill had been contained by a dike and that clean-up was under way. The volume of the spill was initially reported as 10,000 gal.

RELEASE MATERIALS

- How Detected:
- Material Types: 5% solution of PCP in diesel oil.
- Quantities released: 15,000 gal.

RELEASE DURATION: Release occurred on June 14, 1979.

TANK DESIGN AND OPERATING CHARACTERISTICS

- Tank Use: Storage
- Tank Design: 21,000-gallon, steel, horizontal, above-ground, on cradles.
- Equipment that failed: cradles
- Secondary containment: present, but inadequate.

RELEASE ENVIRONMENT

- Land, Water, Air, Unknown: land and water
- Description of Contamination: There was a total fish kill in the farm pond and a threat of overflow into a navigatable river known as a valuable wildlife habitat. Soil along the path of flow was contaminated.

TANK FAILURE CASE STUDY #23

NAME: Howe, Inc.

LOCATION: Brooklyn Center, MN

RELEASE MECHANISM: Hazardous materials carried off-site by smoke from fire and run-off water from fire-fighting efforts.

DATE SOURCE

- United States Environmental Protection Agency, Case Studies 1-23: Remedial Response at Hazardous Waste Sites, EPA-540/2-84-0026, March 1984 (Case Study #14).

DESCRIPTION OF RELEASE

- In January, 1979, a fire occurred at a warehouse site containing 100 different pesticides totaling 80 tons of active ingredients. Water used to fight the fire flowed off-site, carrying with it dissolved pesticides and herbicides. Several additional dangers were involved:

  - Air pollution from combustion of organic solvents. Pigeons flying through the plume died immediately. Eleven fire fighters became ill.

  - Fallout from the plume.

  - Contaminated building debris.

  - Run-off from contaminated soils.

CAUSE OF RELEASE: Faulty acetylene torch

RELEASE MATERIALS

- How detected: immediate visual detection
- Material types: Pesticide- and herbicide-contaminated water; fumes.
- Quantities released: 500,000 gallons of contaminated water; unknown amount of fumes.

RELEASE DURATION: several hours

RELEASE ENVIRONMENTS

- Land, Water, Air, Unknown: land and air
- Description of contamination: Air and land surface. Because of cold temperatures, the contaminated water froze on the ground surface.

TANK FAILURE CASE STUDY #24

NAME: N. W. Mauthe, Inc.

LOCATION: Appleton, Wisconsin

RELEASE MECHANISM: Accidental spills; cracks in concrete floor.

DATA SOURCE

- United States Environmental Protection Agency, Case Studies 1-23: Remedial Response at Hazardous Waste Sites, EPA-540/2-84-0026, March 1984 (Case Study #16).

DESCRIPTION OF RELEASE

- A blower vent for a chrome-plating tank discharged chromium-laden mist to the outside;
- Drippings from chromating tanks were channeled to a sanitary sewer by a trough in the floor. Cracks in the trough and the concrete flooring led to seepage into underlying soil.

CAUSE OF RELEASE

- Poor design and aging of concrete floor

RELEASE MATERIALS

- How Detected: In March, 1982, yellow puddles were observed on adjacent property.
- Material Types: Chromium-contaminated water.
- Quantities released:

RELEASE DURATION

- The shop operated from 1966 through 1976. The releases were probably ongoing through much or all of that time.

RELEASE ENVIRONMENT

- Land, Water, Air, Unknown: land
- Description of contamination: Continuing spills contaminated soils at the site. The contaminants migrated off-site, where they were discovered as "yellow puddles." There was a threat to nearby residences and schools and a threat of run-off to storm sewers leading to the Fox River.

TANK FAILURE CASE STUDY #25

NAME: Quanta Resources

LOCATION: Queens, NY

RELEASE MECHANISM: Vandalism

DATA SOURCE

- United States Environmental Protection Agency, Case Studyes 1-23: Remedial Response at Hazardous Waste Sites, EPA - 540/2-84-0026, March 1984 (Case Study #19).

DESCRIPTION OF INCIDENT

- The facility was a processing facility containing about 500,000 gal. of miscellaneous wastes, including PCB-contaminated oils, cyanides, heavy metals, and low flash-point chlorinated solvents. Bankruptcy of the owner left the facility without security against arson or vandalism.

CAUSE OF RELEASE

- None--no release actually occurred. However, the unguarded state of the facility posed a substantial risk of arson or vandalism.

TANK FAILURE CASE STUDY #26

NAME: White's Septic Tank Services

LOCATION: DuPage County, IL

RELEASE MECHANISM: Operator error

DATA SOURCE

- Landfilling of Special and Hazardous Waste in Illinois: A Report to the Illinois General Assembly, Illinois Legislative Investigating Commission, 1977.

DESCRIPTION OF INCIDENT

- White operated a land treatment facility on his 30-acre farm. He was permitted to accept only domestic septage. He could spread it only in good weather and not near the river. Never- theless, he accepted commercial wastes of unknown nature, mixing them with the septage in his trucks. He professed ignorance of his permit requirements and was "cordial." His record-keeping was virtually non- existent. According to the report, he was "totally lacking in the skill, equipment, knowledge, and desire necessary [for] toxic waste disposal...--blythely spread [ing] industrial wastes over farm land."

COMMENTS

- White had also been in the same business at different times at other Illinois sites.

- This case study does not involve hazardous waste tanks. It is nevertheless relevant, because tank operators can be just as untrained as landfarm operators.

TANK FAILURE CASE STUDY #27

NAME: White's Septic Tank Services

LOCATION: DuPage County, IL

RELEASE MECHANISM: Inspection error

DATA SOURCE

- Landfilling of Special and Hazardous Waste in Illinois: A Report to the Illinois General Assembly, Illinois Legislative Investigating Commission, 1977.

DESCRIPTION OF INCIDENT (see preceding case study)

- An Illinois Department of Public Health inspector made a routine visit to White's landfarm on 7/6/78, accompanied by an Illinois Legislative Investigation Commission observer. The visit involved an application for license renewal. The IDPH inspector:

  - Was uncertain of what the law required;
  - Was unaware of the danger of leachate contaminating river;
  - Took no water samples;
  - Placed a checkmark next to "Inspection of servicing equipment" without ever going near the one truck that made a dump while he was on the site; and
  - Did not seem particularly knowledgeable about the operating requirements.

COMMENTS

- This case study does not involve hazardous waste tanks. It is nevertheless relevant, because similar inspection errors could occur at any type of hazardous waste facility.

TANK FAILURE CASE STUDY #28

NAME: Destructol Carolawn

LOCATION: Kernersville, NC

DATA SOURCE: EPA/SCS Remedial Action Cases, Site D

RELEASE MECHANISM: Catastrophic release (vandalism)

DESCRIPTION OF RELEASE

- On June 3, 1977, vandals opened the valves on six storage tanks at a commercial hazardous waste incinerator. There were no locks on the valves. There was no secondary containment.

RELEASE MATERIALS:

- How Detected: Immediate visual observation
- Material Types:
- Quantities Released: 30,000 gal.

RELEASE ENVIRONNMENT:

- Land, Water, Air, Unknown: land and water
- Description of contamination: There was a 90-99% fish kill in a nearby 50-acre reservoir. 200 local residents were temporarily evacuated. Temporary water rationing and industrial layoffs resulted, as the municipality sought an alternative water source. So far, there has been permanent loss of the reservoir as a drinking water source (the state refused to approve the reservoir as a drinking water source as long as the threat of future contamination remained).