APPENDIX 6.15-1

OFFSITE CONSEQUENCE ANALYSIS

TECHNICAL APPENDIX
OFFSITE CONSEQUENCE ANALYSIS
AVENAL ENERGY PROJECT

1 - Introduction

This Appendix describes the calculation of evaporation rates, and the modeling of the atmospheric dispersion of ammonia for worst-case and alternate-case release scenarios of 19.0 wt% aqueous ammonia. The evaporation rates are used in the DEGADIS dispersion model to compute endpoint distances for the following "Level of Concern " concentration thresholds:

Table 1: Endpoint Concentration Thresholds and Averaging Times

Threshold	Concentration, ppmv	Averaging Time, min.
Lethal	2000	30
Immediately Dangerous to Life and Health (IDLH)	300	30
Emergency Response Planning Guideline – Level 2 (ERPG-2)	200	60
Short Term Public Emergency Limit (STPEL)	75	30

1 – 1: Worst-Case Release Scenario: Instantaneous Spill from 24,000-Gallon Tank

The first scenario concerns the worst-case instantaneous release of 24,000 gallons of 19.0 wt% aqueous ammonia solution into a sloping sump equipped with a 24-inch drain dropping directly into a secondary underground containment vault, whose volume is 28,151 gallons. For the evaporation and dispersion calculations, the meteorological and ground surface roughness conditions that fulfill California Accidental Release Prevention (Cal-ARP) Program requirements are the following:

- Ambient temperature (maximum in previous 6 years): 111 °F
- Relative humidity, average: 55 percent
- Wind Speed: 1.5 m/s
- Stability Class: F
- Roughness Height (rural classification): 0.03 meter

Design features that reduce the potential environmental impacts include the following:

- A secondary outer containment wall surrounds the two identical 24,000-gallon tanks with dimensions of 52 ft by 48 ft (area = 2,496 sq. ft). The wall limits the spread of hypothetically spilled aqueous ammonia, and therefore reduces the area available for ammonia evaporation.
- Inner walls separate the 24 ft by 52 ft sloping sump under each tank (area = 1,248 sq. ft), further limiting the area available for ammonia evaporation.
- A tertiary underground containment vault under the storage tanks collects spilled ammonia and further reduces the area available for evaporation to that of the access drain holes.
- A 24-inch diameter (manhole-size) circular drain shortens the time for the 24,000 gallons of aqueous ammonia to flow into the tertiary underground containment vault
- The sumps contain two layers of hydrophobic high-density polyethylene (HDPE) balls, which will float on the liquid from a hypothetical spill, thereby reducing the surface area of evaporation.
- A grating is placed over each drain to prevent the balls from falling into the vault. The grating reduces the flow area by 25%. For purposes of our calculation, it was assumed that the balls were close-packed (each ball touched six neighboring balls) in a single layer. It is recommended that two or three layers be used, to assure a proper distribution in case some balls are blown around by the wind.
- The underground tertiary containment vault measures:
  - 49 feet in length (perpendicular to the tank long axes)
  - 12.8 feet in width (parallel to the tank long axes)
  - 6 feet in depth

1 – 2: Alternative Release Scenario

This scenario is based on accidentally disconnecting the 3-inch bottom outlet of a tank truck containing 8,000 gallons of 19.0 wt % aqueous ammonia. The aqueous ammonia flows into a 95'4" x 16 ft sloping sump equipped with a 10-inch drain leading to the same vault described in the worst-case scenario. For the evaporation and dispersion calculations, the meteorological and ground surface roughness conditions that fulfill Cal-ARP Program requirements are the following:

• Ambient temperature, average:	64 °F
• Relative humidity, average:	55 percent
• Wind Speed, average:	2.5 m/s
• Stability Class, average:	D
• Roughness Height (rural classification):	0.03 meter

Unlike the instantaneous worst-case spill, liquid does not accumulate in the sump, but is assumed to flow in a rectangular "falling film". Although the liquid "sheet" may become narrower as it approaches the drain, the calculations were simplified by assuming that the falling film covers half the area of the sump (an overestimate), and that ammonia evaporates at a constant rate until the tank truck is empty.

2 – Evaporation Rate Calculation Method

2 – 1: EPA Offsite Consequence Analysis Guidance Equation

The EPA *Risk Management Program Guidance for Offsite Consequence Analysis* (Equation D-1, page D-2, April 15, 1999) gives the following equation for calculating the evaporation rate of a volatile toxic compound from a liquid pool:

$$E = \frac{0.284u^{0.78}M^{2/3}AP_v}{82.05T} \qquad \text{(Eq. 1)}$$

where:

E = Evaporation rate, lb/min
u = Wind speed, m/s
M = Pollutant molecular weight, lbs/lb-mole
A = Pool area, ft^2
P_v = Vapor pressure of pollutant, mmHg
T = Pool temperature, °K

2 – 2: Partial Pressures of Ammonia over Aqueous Ammonia Solutions

For an aqueous ammonia solution, the variable P_v in Equation 1 is replaced by the partial pressure of ammonia over the solution. Aqueous ammonia is a highly non-ideal solution (i.e., partial pressures are not proportional to mole fractions), so partial pressures of ammonia and water were interpolated from tabular data found in *Perry's Chemical Engineers' Handbook* (Tables 3-21 and 3-23, pages 3-71 and 3-72, Sixth Edition, see Attachment A).

In these tables, partial pressures are given in psia (pounds per square inch absolute) for intervals of 5 mole percent ammonia concentration, and intervals of 10°F from 40°F to 250°F. Ammonia concentrations in weight fraction are converted to mole fraction as follows:

$$x = \frac{w/M_a}{\frac{w}{M_a} + \frac{1-w}{M_w}} \qquad \text{(Eq. 2)}$$

where:

x = mole fraction ammonia (= mole percent ammonia / 100 percent)
w = weight fraction ammonia (= weight percent ammonia / 100 percent)
M_a = molecular weight of ammonia = 17.03 lb/lb-mole
M_w = molecular weight of water = 18.016 lb/lb-mole

In general, partial pressures do not vary linearly with temperature, but over small temperature ranges, they tend to obey the Clausius-Clapeyron equation:

$$\ln P_v = A - \frac{B}{T} \qquad \text{(Eq. 3)}$$

where:

T = absolute temperature (°K)
A and B are constants.

For the Avenal Energy Project scenarios, partial pressures were required for a temperature of 64°F, which was interpolated between tabulated values at 60° and 70°F, and a temperature of 111°F, which was interpolated between 110° and 120°F. All Fahrenheit temperatures were converted to absolute temperatures in degrees Kelvin as follows:

$$T = \frac{(F-32)}{1.8} + 273.15 \qquad \text{(Eq. 4)}$$

where F = temperature in degrees Fahrenheit.

For a given mole fraction ammonia, if partial pressures P_1 and P_2 are obtained for two absolute temperatures T_1 and T_2 which "straddle" the desired temperature, Equation 3 can be applied twice and solved for the constants A and B:

$$B = \frac{T_1 T_2}{T_2 - T_1} \ln\left(\frac{P_2}{P_1}\right) \qquad \text{(Eq. 5)}$$

$$A = \ln P_1 + \frac{T_2}{T_2 - T_1} \ln\left(\frac{P_2}{P_1}\right) \qquad \text{(Eq. 6)}$$

Once A and B are known, they are substituted back into Equation 3 to calculate the partial pressure at the intermediate temperature.

This procedure was repeated at 64°F and 111°F for all ammonia mole fractions from zero to 35 percent in increments of 5 percent, for partial pressures of both ammonia and water. Partial pressures were converted from psia to mmHg by multiplying by (760 mmHg/atm) / (14.696 psia/atm).

Least-squares regressions were then performed for partial pressure of each compound (ammonia and water) as a function of mole fraction at each temperature (64°F and 111°F). For ammonia, the regressions were cubic, of the form:

$$P_a = ax + bx^2 + cx^3 \qquad \text{(Eq. 7)}$$

while for water, a linear regression was used:

$$P_w = a + bx \qquad \text{(Eq. 8)}$$

Table 2 summarizes the coefficients resulting from these regressions, where partial pressures are in mmHg, and x is in mole percent:

Table 2: Partial Pressures as Functions of Mole Percent Ammonia

Compound	Temperature, °F	*a*	*b*	*c*
Ammonia	64	8.643	-0.3904	0.02313
	111	23.745	-0.7033	0.04623
Water	64	15.18	-0.1628	Not Applicable
	111	67.65	-0.7211	Not Applicable

2 – 3: Densities of Aqueous Ammonia Solutions

The density of aqueous ammonia solution depends strongly on ammonia fraction, and slightly on temperature. This variation is taken into account when calculating pool volume, which affects the evaporation area in a sloping sump.

Tabular density data (in g/cm^3) is available in *Perry's Chemical Engineers' Handbook* (Table 3-32, page 3-79, Sixth Edition, see Attachment A) at 10°C (50°F) and 20°C (68°F) for ten ammonia concentrations ranging from 1 to 30 wt%. Additional data is obtained from standard "steam tables" for pure water, which extends the range down to zero weight percent ammonia. These data were regressed as functions of weight percent ammonia (w) as follows:

$$\rho = a + bw + cw^2 \qquad \text{(Eq. 9)}$$

where the coefficients *a, b,* and *c* have the values shown in Table 3:

Table 3: Density of Aqueous Ammonia Solution as a Function of Weight % Ammonia

Temperature, °C (°F)	*a*	*B*	*c*
10 (50)	0.9993	$-4.099(10^{-3})$	$2.476(10^{-5})$
20 (68)	0.9979	$-4.249(10^{-3})$	$2.431(10^{-5})$

Density can be interpolated or extrapolated with sufficient accuracy as a linear function of temperature. Densities were calculated at 10°C (50°F) and 20°C (68°F) using Equation 9. These densities were then interpolated to 64°F, while the density at 68°F was linearly extrapolated to 111°F.

3 – Mass Balance Calculations in Sloping Sumps

3 – 1: Introduction

Cal-ARP requires that the worst-case scenario for a toxic mixture stored at atmospheric pressure (such as aqueous ammonia) be the hypothetical instantaneous spill of the total content of the single largest storage vessel, followed by volatilization of the hazardous material.

Aqueous ammonia storage at the Project will comprise two tanks, each holding 24,000 gallons mounted over its own rectangular sump 52 feet long by 24 feet wide. A 24-inch diameter ("manhole") circular drain will be located at the center of the sloping bottom of each sump. The drain will drop directly into a 28,151-gallon vault, which is sized to contain both the 24,000 gallons of aqueous ammonia and the 25-year repeat interval 24-hour maximum precipitation event. The minimum slope of the bottom of the sump is assumed to be 1 inch vertical drop per 6 feet horizontal distance, or $^{1}/_{72}$. The bottom of each sump is assumed to be four triangles, whose edges run outward and slightly upward from the drain to each corner of the sump. The geometrical shape of the bottom of the sump is an inverted rectangular pyramid. The slope and shape of the bottom affect the last part of the drainage of the instantaneously released 24,000 gallons.

The two sumps are arranged side-by-side along the longer edge, so that together they form a 52 ft x 48 ft rectangle, surrounded by a retaining wall. Separator walls surround each 52 ft x 24 ft sump to contain the 24,000 gallon release.

If 24,000 gallons of ammonia are spilled instantaneously into such a containment, the liquid level will rise to the height that holds 24,000 gallons, including the volume in the inverted pyramid. Liquid will then flow into the drain at a rate that depends on the height of the liquid above the drain, which decreases with time. At the same time, ammonia and water will evaporate from the liquid surface. Ammonia will evaporate faster, resulting in a decrease in ammonia concentration with time. When the liquid level reaches the sloping part of the containment, the surface area will also decrease with time. Evaporation rates of ammonia and water depend on surface area and partial pressure as shown in Equation 1, and hence, will vary with time.

To handle several time-varying parameters, mass balances were calculated for time steps short enough so that liquid properties only change slightly during each step. Outflow rates and evaporation rates are calculated using the parameters at the start of each time step. The masses of ammonia and water at the end of the time step are obtained by mass balance.

The density and partial pressures are recalculated; the new volume is calculated from the mass and the density; and the new liquid height is calculated from the new volume and area of the sump. Parameter values at the end of a time step are used to start the next time step. The process is repeated until the liquid level reaches the drain.

3 – 2: Liquid Height and Volume

The sloping sumps are 52 feet long and 24 feet wide at the top, converging to a circular drain at the bottom, whose diameter is 24 inches. To simplify the flow geometry between a rectangular sump and a circular drain, the shape of the drain was assumed to be a square with the same area as a 24-inch diameter circular drain. Its side length would be given by

$$L_d^{\,2} = \frac{\pi D_d^{\,2}}{4}, \text{ or}$$

$$L_d = D_d \frac{\sqrt{\pi}}{2} \qquad \text{(Eq. 10)}$$

The slope of the sump from the edge of the drain to the end of the sump is assumed to be 1 inch per 6 feet, or $^1/_{72}$. The edge of the drain is a distance $L_d/2$ from the centroid of the sump, while the edge of the sump is a distance $L_s/2$, where L_s = 52 feet, the length of the top of the sump. The depth of the sump is therefore $^1/_{72}$ of the distance $(L_s - L_d)/2$, or

$$H_s = \frac{L_s - L_d}{144} \qquad \text{(Eq. 11)}$$

As the liquid level rises from $z = 0$ (at the drain) to $z = H_s$, the length between the sloping sides increases linearly from L_d to L_s, so that

$$L(z) = L_d + (L_s - L_d)\frac{z}{H_s} = L_d + 144z \qquad \text{(Eq. 12)}$$

where H_s was substituted from Equation 11.

Along a vertical plane running through the drain across the short side of the sump, the width between sloping sides increases linearly from L_d at $z = 0$ (the drain) to W_d = the width of the top of the sump = 24 feet, at $z = H_s$. The width as a function of liquid height is thus given by:

$$W(z) = L_d + (W_s - L_d)\frac{z}{H_s} \qquad \text{(Eq. 13)}$$

If the horizontal cross-section is assumed rectangular at all levels, the area is given by:

$$A(z) = L(z)W(z) = L_d^{\,2} + \frac{(L_s + W_s - 2L_d)L_d z}{H_s} + \frac{(L_s - L_d)(W_s - L_d)z^2}{H_s^{\,2}} \qquad \text{(Eq. 14)}$$

This can be simplified to:

$$A(z) = L_d^{\,2} + (\lambda + \omega)L_d z + \lambda\omega z^2 \qquad \text{(Eq. 15)}$$

where:

$$\lambda = \frac{L_s - L_d}{H_s} = 144 \qquad \text{(Eq. 16)}$$

$$\omega = \frac{W_s - L_d}{H_s} \qquad \text{(Eq. 17)}$$

The volume from the drain up to a liquid level z is obtained by integrating the area function:

$$V = \int_0^z A(z)dz = L_d^{\,2} z + \frac{(\lambda + \omega)L_d z^2}{2} + \frac{\lambda\omega z^3}{3} \qquad \text{(Eq. 18)}$$

It should be noted that Equation 18 is only valid for the sloping portion of the sump, where $z < H_s$. The total volume of the sloping portion of the sump is given by substituting $z=H_s$ into Equation 18. Combining Equations 16, 17, and 18 gives the following relationship:

$$V_s = \frac{H_s}{3}\left[L_d^{\,2} + L_s W_s + \frac{L_d(L_s + W_s)}{2}\right] \qquad \text{(Eq. 19)}$$

If the liquid level is higher than the top of the sloping portion of the sump, the volume above the sloping portion is equal to the area $L_s W_s$ times the liquid height above the sloping portion (z-H_s), or

$$V_{top} = L_s W_s (z - H_s) \qquad \text{(Eq. 20)}$$

The total volume is obtained by adding Equations 19 and 20, or:

$$V_T = V_s + V_{top} = L_s W_s\left(z - \frac{2H_s}{3}\right) + \frac{H_s L_d}{6}\left(L_s + W_s + 2L_d\right) \qquad \text{(Eq. 21)}$$

If there were no walls between the two sumps, the total volume would be obtained by multiplying the volume above one sump (Equation 18 if $z<H_s$, Equation 21 if $z>H_s$) by the number of sumps N_s=2. Without separator walls, the total surface area for evaporation A(z) (from Equation 15) would also be multiplied by $N_s = 2$. Because walls separate the sumps and are high enough to contain the volume of a tank in one sump, $N_s = 1$.

In the actual mass-balance calculation, the total mass and density are calculated at the end of a time step, from which the remaining liquid volume V_T can be obtained, but the liquid height z is unknown. If this volume is greater than that of the sloping part of the sumps V_s, Equation 21 can be solved explicitly for z. However, if $V_T < V_s$, Equation 18 is cubic in z, and hence, the liquid height z is calculated iteratively, using the "Goal Seek" function in Microsoft Excel to converge the volume to within 1 cm^3.

It should be noted that all quantities are converted to metric units in order to simplify calculations, although a separate pool area is calculated in square feet, to be used in the evaporation rate Equation 1.

Table A – 1 in Appendix A shows the calculations used to obtain the initial liquid height when 24,000 gallons of aqueous ammonia are spilled into the sloping sump. The depth of the sloping part of the sump (H_s = 0.1058 m = 4.17 inches) was obtained from Equation 11. From this value, and the dimensions at the top of the sump, the parameters $\lambda = 144$ and $\omega = 63.36$ were calculated from Equations 16 and 17, respectively. Substituting these values into Equation 19 results in a volume of 4.352 m^3, or 1,150 gallons, for the sloping part of the sump.

Setting the total liquid volume to 24,000 gallons = 90.85 m^3 and solving Equation 21 iteratively for the total liquid height results in $z = 0.8519$ meter = 33.54 inches.

3 – 3: Calculation of Liquid Outlet Rate through Drain

The flow rate of aqueous ammonia through the drain is calculated by a simplified energy balance over the liquid in the sump, whereby gravitational potential energy is assumed to be completely converted into the kinetic energy of the liquid leaving through the drain. In this energy balance, the following assumptions are made:

1) The pressure inside the vault below the drain is assumed equal to the pressure at the liquid surface.

2) Only the vertical (downward) component of fluid velocity is taken into account. This assumption is valid while the liquid level is above the sloped lower portion of the sump. When the liquid level is in the sloped portion, the liquid flow converges toward the drain, causing horizontal flow along the bottom with friction. The horizontal flow with friction would increase the energy loss and slightly reduce the outlet flow rate, and thereby increase the time during which liquid in the sloping sump is exposed to evaporation. The difference in total time would be minimal because the volume of the sloped portion of the sump is only 4.8% of the total liquid volume spilled.

With the previous assumptions in mind, the following variables are defined:

v_d = velocity of liquid through the drain
P_d = pressure of liquid at the drain
ρ_d = density of liquid at the drain
z = height of liquid surface above the drain
A(z) = area of top surface of liquid in the sump
P(z) = pressure at liquid surface (= atmospheric pressure)
v(z) = vertical velocity of liquid at its surface
ρ(z) = density of liquid at its surface

The energy balance for frictionless flow (Bernoulli equation) is as follows:

$$P(z) + \rho(z)gz + \frac{\rho(z)v(z)^2}{2} = P_d + \frac{\rho_d v_d^2}{2} \qquad \text{(Eq. 22)}$$

where g = the acceleration of gravity = 9.80665 m/s^2.

If the pressures and liquid densities at the liquid surface and the drain are assumed to be equal ($P(z) = P_d$, $\rho(z) = \rho_d$), this equation simplifies to:

$$gz = \frac{\left(v_d^{\,2} - v(z)^2\right)}{2} \qquad \text{(Eq. 23)}$$

If, as a good approximation, the rate of evaporation is assumed to be much less than the liquid flow rate through the drain, the volume rate of liquid leaving the drain can be assumed equal to the rate of volume decrease at the surface of the sump:

$$A(z)v(z) = \frac{\pi D_d^{\,2} v_d}{4} = A_d v_d \qquad \text{(Eq. 24)}$$

where $A_d = \pi D_d^2/4$ is the open area of the drain. Solving for v(z) results in:

$$v(z) = \frac{v_d A_d}{A(z)} \qquad \text{(Eq. 25)}$$

Substituting this into Equation 23 and solving for v_d results in:

$$v_d = \sqrt{\frac{2gz}{\left[1 - \left(\frac{A_d}{A(z)}\right)^2\right]}} \qquad \text{(Eq. 26)}$$

Once the liquid velocity in the drain, v_d, is calculated, the mass flow rate of liquid leaving the drain can be calculated as:

$$Q_d = \rho A_d v_d = \rho A_d \sqrt{\frac{2gz}{\left[1 - \left(\frac{A_d}{A(z)}\right)^2\right]}} \qquad \text{(Eq. 27)}$$

It should be noted that while g and A_d are constants, the liquid height z decreases with time, the surface area A(z) decreases with time when the liquid level is in the sloping part of the sump ($z < H_s$), and the liquid density ρ varies slowly with time due to the gradual evaporation of ammonia. Each of these variables can be approximated as being constant over a short time step in order to simplify calculations, but needs to be updated at the end of each time step, to determine its new value for the next time step.

3 – 4: Liquid Mass Balance over a Time Step

If, for a given time step Δt, the evaporation rates of both ammonia and water, as well as the outlet flow rate through the drain can be calculated using the methods given in the previous section, two mass balances (for ammonia and water) can be written in the following form:

Final Mass = Initial Mass – Mass through Drain – Mass Evaporated (Eq. 28)

Let:

m_1 = mass of aqueous ammonia solution in sump at start of time step, lb
w_1 = weight fraction ammonia in solution at start of time step
m_2 = mass of aqueous ammonia solution in sump at end of time step, lb
w_2 = weight fraction ammonia in solution at end of time step
E_a = evaporation rate of ammonia during time step, lb/min
E_w = evaporation rate of water during time step, lb/min

The evaporation rates for ammonia and water are calculated by substituting the appropriate properties into Equation 1:

$$E_a = \frac{0.284u^{0.78}M_a^{2/3}A(z)P_a}{82.05T} \qquad \text{(Eq. 29)}$$

$$E_w = \frac{0.284u^{0.78}M_w^{2/3}A(z)P_w}{82.05T} \qquad \text{(Eq. 30)}$$

where:

M_a = molecular weight of ammonia = 17.03 lb/lb-mole
M_w = molecular weight of water = 18.016 lb/lb-mole
P_a = partial pressure of ammonia, from Equation 7, mmHg
P_w = partial pressure of water, from Equation 8, mmHg

Equation 1 requires pool area to be given in square feet, and expresses evaporation rate in pounds per minute. The DEGADIS dispersion model requires emission rates in kg/s, and calculations are easier if such metric units are used consistently. If A(z) is given in square meters, and E_a or E_w are to be obtained in kg/s, then the 0.284 factor in Equations 29 and 30 must be multiplied by

$$\left(\frac{1ft}{0.3048m}\right)^2\left(\frac{1kg}{2.2046lb}\right)\left(\frac{1\min}{60\sec}\right) = 0.081375.$$

Multiplying 0.284 by 0.081375, then dividing by the 82.05 factor in Equation 1 (the ideal gas constant R in atm-cm^3/gmol°K) results in a single factor 2.81662(10^{-4}), from which:

$$E_a = \frac{2.81662(10^{-4})u^{0.78}M_a^{\ 2/3}A(z)P_a}{T} \qquad \text{(Eq. 31)}$$

$$E_w = \frac{2.81662(10^{-4})u^{0.78}M_w^{\ 2/3}A(z)P_w}{T} \qquad \text{(Eq. 32)}$$

where all quantities are in *Système International* (SI) units except the partial pressures, which are given in millimeters of mercury (mmHg).

With E_a and E_w in consistent units, the overall mass balance (ammonia + water) can be written:

$$m_2 = m_1 - Q_d\Delta t - E_a\Delta t - E_w\Delta t \qquad \text{(Eq. 33)}$$

For any given time step, it is assumed that m_1 and w_1 are known. For the first time-step, these are equal to the initial mass spilled, and weight-fraction ammonia prior to the spill. From the initial mass fraction w_1, the initial mole fraction x_1 is calculated using Equation 2, the partial pressures P_a and P_w are calculated using Equations 7 and 8, and the initial solution density ρ_1 is calculated using Equation 9.

Dividing the initial mass, m_1, by the solution density, ρ_1, gives the initial volume, V_1. If this volume is greater than V_s, the volume of the sloping part of the sump, the liquid height z is obtained explicitly by solving Equation 21 for z; if not, it is obtained by iteratively solving Equation 18 using the "Goal Seek" option in Microsoft Excel. The surface area of the liquid A(z) is then obtained either by substituting into Equation 15 (if $z < H_s$), or by $A(z) = L_sW_s$ (if $z > H_s$, this is the area of the top of the sump).

Once z and A(z) are known, the liquid outlet flow through the drain Q_d is obtained using Equation 27, and the evaporation rates for ammonia (E_a) and water (E_w) are obtained from Equations 31 and 32, respectively. These values are substituted into the overall mass balance (Equation 33) to obtain the final mass m_2 at the end of the time step.

The mass fraction ammonia w_2 at the end of the time-step is obtained by a mass balance over the ammonia evaporating from and leaving the sump through the drain:

$$m_2w_2 = m_1w_1 - Q_dw_1\Delta t - E_a\Delta t \qquad \text{(Eq. 34)}$$

from which:

$$w_2 = \frac{m_1 w_1 - Q_d w_1 \Delta t - E_a \Delta t}{m_2} \qquad \text{(Eq. 35)}$$

where m_2 is given by Equation 33. Once m_2 and w_2 are calculated, they are assumed to be the corresponding values of m_1 and w_1 for the next time step, and the process is repeated until the sump is empty ($m_2 = 0$).

Many of the parameters used to calculate Q_d, E_a, and E_w vary with time. The time step Δt is chosen small enough to make the difference between average values over each time step and initial values acceptably small. In practice, Δt was chosen as a compromise between accuracy and calculation time. The iterative calculation of the liquid height was performed automatically using the Goal Seek feature, but the command used to invoke this feature was entered manually for each time step. Smaller time steps were used as the liquid level approached the bottom of the sump ($z \rightarrow 0$), because the liquid surface area A(z) varies rapidly in that portion. A second iterative procedure adjusted the final time step until the final mass in the sump was approximately zero.

3 – 5: Reduced Evaporation Area using HDPE Balls

TRC discussed with the Commission other design features that could further reduce evaporation rate and endpoint distances. One suggestion was covering the bottom of the containment sump with impermeable balls, made of a plastic material less dense than aqueous ammonia. In the event of a spill, the balls would float on the surface of the solution, thereby reducing the area available for evaporation.

If the density of the balls was too high (more than half that of aqueous ammonia solution), then a single layer of balls may not provide optimum reduction of the evaporation area. Enough layers will be used to assure that the balls adjacent to the liquid surface will be "close-packed". This arrangement will minimize the area available for evaporation.

To calculate the effective area available for evaporation, a "close-packed" layer is assumed to be arranged such that each ball in a given horizontal plane touches six of its neighbors, with the six "touching points" forming a regular hexagon around the ball's center. The lines from the center of a ball to the six "touching points" form 60° angles with each other. If this pattern is repeated, the centers of any three mutually tangent balls are the vertices of an equilateral triangle of side length $2r$, where r is the radius of the balls.

The altitude of an equilateral triangle is given by:

$$h = 2r\frac{\sqrt{3}}{2} = r\sqrt{3} \qquad \text{(Eq. 36)}$$

and its area is:

$$A_t = \frac{bh}{2} = \frac{(2r)\left(r\sqrt{3}\right)}{2} = r^2\sqrt{3} \qquad \text{(Eq. 37)}$$

The area open for evaporation is equal to the area of the triangle less the area blocked by the projected area of the balls. Within this triangle, each ball blocks $^1/_6$ of its projected area πr^2, but there are 3 balls each blocking this same projected area. The total blocked area is:

$$A_b = \left(\frac{3}{6}\right)\pi r^2 = \frac{\pi r^2}{2} \qquad \text{(Eq. 38)}$$

The ratio of the open area (available for evaporation) to the total pool area is equal to the area of the triangle less that of the blocked area, divided by the area of the triangle, or:

$$\alpha = \frac{A_t - A_b}{A_t} = \frac{r^2\sqrt{3} - \pi r^2/2}{r^2\sqrt{3}} = 1 - \frac{\pi}{2\sqrt{3}} \approx 0.0931 \qquad \text{(Eq. 39)}$$

The presence of a close-packed layer of balls above the liquid surface thus limits the evaporation area to about 9.3% of the liquid surface area. Theoretically, this area ratio does not depend on the radius of the balls.

In reality, the area ratio is slightly larger than that given by Equation 39, because the balls will not be close-packed at the edges of the sump. For this reason, the ball diameter will be much less than the sump width to keep these "non-close-packed" areas negligible compared to the sump area, but the balls must be large enough so they will not be easily blown about by the wind. A diameter of 2 to 3 inches is a reasonable compromise between these two requirements.

Although the area available for evaporation might be under-estimated slightly using by Equation 39, this error is probably compensated by the fact that the wind speed across the liquid surface is assumed equal to that in free ambient air. In reality, the flow of air across the liquid surface is probably slowed down considerably due to frictional effects of air passing between the balls. Although this effect is difficult to quantify, it is probably of greater importance than the underestimation of α due to edge effects, so the overall evaporation rate is probably overestimated, leading to overestimated endpoint distances.

3 – 6: Reduced Drain Area due to Grating

Because the sumps will be covered with HDPE balls, the drains will be covered with gratings, whose mesh is smaller than the ball diameter, to prevent the balls from falling into the underground vault. The presence of these gratings reduces the drain area, thereby slowing down the flow of aqueous ammonia through the drain, and increasing the time during which ammonia evaporates from the surface of the liquid in the sump.

If the gratings are assumed to consist of wire squares whose side length is s, bounded by wires of diameter d_w, the total area of each square is s^2. The area blocked by the wires around each square is equal to the perimeter $4s$ multiplied by the wire diameter d_w. However, each wire blocks part of the area occupied by the two squares on either side, so the area blocked by the wires for each square is only half the total wire area, or $2sd_w$. The ratio of open area available for flow to the total drain area is thus:

$$\beta = \frac{OpenArea}{DrainArea} = \frac{SquareArea - WireArea}{SquareArea} = \frac{s^2 - 2sd_w}{s^2} = 1 - \frac{2d_w}{s} \qquad \text{(Eq. 40)}$$

The grating is assumed to consist of 1-inch squares with wires $^1/_8$ inch in diameter, for which $\beta = 0.75$. These calculations are performed as described in Section 3-4, except that the evaporation area A(z) is replaced by $\alpha A(z)$, and the drain area A_d is replaced by βA_d.

Table A-2 in Appendix A shows the detailed calculations of the outflow rate from the sump, and evaporation rates of ammonia and water from the liquid surface as a function of time, according to the methods described in Sections 3-3 through 3-6.

3 – 7: Evaporation of Ammonia into Vault Headspace

The volume rate at which aqueous ammonia drains into the vault is exactly matched by the volume rate at which vault headspace air is pushed out. This air contains ammonia vapor from the continuous process of ammonia evaporating from the solution. The displaced air is assumed to exit through the other 24-inch diameter drain during the time the liquid solution enters through one drain.

For calculation purposes, the vault is assumed to be 49 feet long, 12.8 feet wide, and 6 feet deep; hence, its total volume is 28,151 gallons. To use Equation 1 to calculate the evaporation rate of ammonia from the solution as it drains into the vault, the velocity of air over the liquid surface must be calculated. The vault is considered to a circle whose total area is equal to that of the vault, with the drain at the center of the circle. The air, displaced upward by the rising liquid, is assumed to flow radially inward toward the drain, with the highest velocities closest to the drain. At a given time, and a given distance from the drain, the air velocity is assumed uniform with height in the vault.

If the vault area $L_v W_v$ is simulated as a circle having the same total area:

$$\pi R_c^{\,2} = L_v W_v \qquad \text{(Eq. 41)}$$

the equivalent radius of each circle is given by

$$R_c = \sqrt{\frac{L_v W_v}{\pi}}\,, \qquad \text{(Eq. 42)}$$

For a vault of length L_v = 49 ft = 14.94 m, and width W_v = 12.8 ft = 3.90 m, the equivalent circle radius becomes R_c = 4.31 m.

If ammonia solution is entering the vault at a mass rate of Q_d kg/s, it displaces air at a volume rate of $q = Q_d / \rho$ m^3/s, where ρ is the density of the ammonia solution. The liquid level rises at a rate equal to the volume rate divided by the vault area, or:

$$\frac{dH_a}{dt} = -\frac{q}{L_v W_v} = -\frac{q}{\pi R_c^{\,2}} \qquad \text{(Eq. 43)}$$

In this equation, H_a represents the height of vapor space remaining in the vault: as liquid enters the vault, this height decreases with time, which is indicated by the negative sign on the right side of Equation 43.

In order to use Equation 1 to calculate the ammonia evaporation rate into the vault, the velocity profile must be obtained over the area of the vault. This calculation is very complex for a rectangular vault, which is why the vault area is simulated as a circle centered at the open drain (other than the drain into which liquid is flowing).

A volume balance is performed around a cylindrical ring of height H_a, inner radius r, and thickness dr, and air is assumed to be flowing radially inward toward the center at a velocity v, which depends on the radius r from the drain. The volume rate of entering the outside of the ring is given by:

$$\left(\frac{dV}{dt}\right)_{in} = 2\pi H_a (r + dr) v_{r+dr} \qquad \text{(Eq. 44)}$$

while the volume rate leaving the inside of the ring is given by:

$$\left(\frac{dV}{dt}\right)_{out} = 2\pi H_a r v_r \qquad \text{(Eq. 45)}$$

The volume available for air inside the ring is decreasing at a rate of:

$$\frac{dV}{dt} = 2\pi r dr \frac{dH_a}{dt} \qquad \text{(Eq. 46)}$$

Substituting for dH_a/dt from Equation 43 results in:

$$\frac{dV}{dt} = -\frac{2qrdr}{R_c^2} \qquad \text{(Eq. 47)}$$

Setting up the volume balance (Air rate in) —(Air rate out) = (rate of volume decrease) results in:

$$2\pi H_a \left[(r + dr) v_{r+dr} - r v_r\right] = -\frac{2qrdr}{R_c^2} \qquad \text{(Eq. 48)}$$

Dividing this by $2\pi r H_a\, dr$ results in:

$$r\left[\frac{v_{r+dr} - v_r}{dr}\right] + v_{r+dr} = -\frac{qr}{\pi H_a R_c^2} \qquad \text{(Eq. 49)}$$

Taking limits as dr →0 results in:

$$r\frac{dv}{dr}+v=\frac{d}{dr}(rv)=-\frac{qr}{\pi H_a R_c^2} \qquad \text{(Eq. 50)}$$

Integrating with respect to r results in

$$rv=-\frac{qr^2}{2\pi H_a R_c^2}+C_1 \qquad \text{(Eq. 51)}$$

where C_1 is a constant of integration independent of radius r. This constant can be evaluated by assuming the inward radial air velocity to be zero at the vault wall ($v = 0$ at $r=R_c$). Substituting this into Equation 51 results in

$$C_1=\frac{q}{2\pi H_a} \qquad \text{(Eq. 52)}$$

Substituting this back into Equation 51 and dividing by r results in the velocity profile:

$$v=\frac{q}{2\pi H_a}\left(\frac{1}{r}-\frac{r}{R_c^2}\right) \qquad \text{(Eq. 53)}$$

The ammonia evaporation rate over an element of surface area dA = $2\pi r\ dr$ can be obtained by substituting v for u and $A = 2\pi r\ dr$ into Equation 31, to obtain:

$$dE_a = Kv^{0.78} 2\pi r dr \qquad \text{(Eq. 54)}$$

where

$$K = \frac{2.81662(10^{-4}) M_a^{\ 2/3} P_a}{T} \qquad \text{(Eq. 55)}$$

It should be noted that the partial pressure of ammonia P_a varies with <u>time</u> as solutions of varying composition enter the vault, but this would not vary as a function of radial <u>distance</u> from the drain at a given instant, and can be considered constant in an integration over the vault area at a given instant.

The total evaporation rate is obtained by integrating Equation 54 over the entire vault area, or a circle of radius R_c:

$$E_a = 2\pi K \int_0^{R_c} v^{0.78} r dr \qquad \text{(Eq. 55)}$$

Substituting for v from Equation 53, and factoring constant terms out of the integral sign results in:

$$E_a = K(2\pi)^{0.22} \left(\frac{q}{H_a}\right)^{0.78} \int_0^{R_c} \left(\frac{1}{r} - \frac{r}{R_c^{\ 2}}\right)^{0.78} r dr \qquad \text{(Eq. 56)}$$

The integral in Equation 56 can be simplified by introducing the dimensionless variable

$$x = \frac{r}{R_c} \qquad \text{(Eq. 57)}$$

from which:

$$r = R_c x$$
$$dr = R_c dx \qquad \text{(Eq. 58)}$$

Substituting Equations 57 and 58 into Equation 56 results in:

$$E_a = K(2\pi)^{0.22}\left(\frac{q}{H_a}\right)^{0.78}\int_0^1\left(\frac{1}{R_c x}-\frac{R_c x}{R_c^{\,2}}\right)^{0.78}(R_c x)(R_c dx)$$

$$= K(2\pi)^{0.22}\left(\frac{q}{H_a}\right)^{0.78}\int_0^1\left(\frac{1-x^2}{x}\right)^{0.78}\left(\frac{R_c^{\,2}}{R_c^{\,0.78}}\right)x dx$$

$$= KR_c(2\pi R_c)^{0.22}\left(\frac{q}{H_a}\right)^{0.78}\int_0^1 x^{0.22}\left(1-x^2\right)^{0.78}dx \qquad \text{(Eq. 59)}$$

In this form, all dimensional and time-varying quantities have been factored out of the integral sign, and the integral in Equation 59 is a constant, dimensionless number which does not vary with time, and therefore only has to be evaluated once.

This integral was evaluated numerically using Simpson s Rule (parabolic curve-fit over each set of three successive points) over 1000 equal increments, and found to be:

$$I = \int_0^1 x^{0.22}\left(1-x^2\right)^{0.78}dx \approx 0.275174. \qquad \text{(Eq. 60)}$$

The evaporation rate of ammonia from the liquid pool into the air in the vault is therefore equal to

$$E_a = 0.275174KR_c^{\,1.22}(2\pi)^{0.22}\left(\frac{q}{H_a}\right)^{0.78} \qquad \text{(Eq. 61)}$$

It should be stressed that this quantity varies with time, as the volume flow rate into the drain ($q = Q_d / \rho$), the height of the vault unoccupied by liquid (H_a), and K (which contains the partial pressure of ammonia over the liquid) all vary with time.

3 — 8: Mass Balance over Liquid in Vault

Let m_{v1} represent the initial mass of liquid in the vault at the start of time step Δt (for the first time-step, starting at $t = 0$, $m_{v1} = 0$. Let w_{v1} represent the weight fraction ammonia in the liquid in the vault.

If liquid aqueous ammonia solution is entering the vault at a mass rate Q_d throughout the time-step, the total mass of solution at the end of the time-step is given by

$$m_{v2} = m_{v1} + Q_d \Delta t \qquad \text{(Eq. 62)}$$

If the liquid entering the vault through the drain from the sump contains a weight fraction ammonia w_1 at the start of the time-step, and w_2 at the end of the time-step, the weight frac-tion ammonia in the liquid in the vault at the end of the time-step w_{v2} can be calculated by an ammonia mass balance:

$$m_{v2} w_{v2} = m_{v1} w_{v1} + \frac{Q_d \Delta t (w_1 + w_2)}{2} \qquad \text{(Eq. 63)}$$

The final ammonia mass fraction, obtained by dividing $m_{v2}w_{v2}$ by the final mass m_{v2} from Equation 62, does not include the possible effects of evaporation from the surface of the liquid in the vault.

The density ρ_v of the solution in the vault is obtained by substituting w_{v2} for w in Equation 9. The liquid depth z_v in the vault is then obtained by dividing the mass of liquid in the vault by its density and the surface area of the vault:

$$z_v = \frac{m_{v2}}{\rho L_v W_v} \qquad \text{(Eq. 64)}$$

The headspace height H_a (height of the vault unoccupied by liquid) is obtained by subtracting the liquid height from the total vault height:

$$H_a = H_v - z_v \qquad \text{(Eq. 65)}$$

The partial pressures of ammonia P_a and water P_w above the liquid in the vault are obtained by calculating the mole fraction ammonia in the liquid using Equation 2 (substituting w_{v2} for w), then using Equations 7 and 8, respectively. These values are then inserted into Equation 55 to obtain a value for K for water and ammonia. The evaporation rates of both ammonia (E_{av}) and water (E_{wv}) are then calculated using the appropriate value of K in Equation 61.

The final mass of liquid in the vault must then be corrected for the total mass evaporated:

$$m_{v2} = m_{v1} + (Q_d - E_{av} - E_{wv})\Delta t \qquad \text{(Eq. 66)}$$

In the same manner, the final weight fraction ammonia in the liquid must be corrected for the ammonia evaporated during the time step:

$$w_{v2} = \frac{m_{v1}w_{v1} + Q_d\Delta t\left(\frac{w_1 + w_2}{2}\right) - E_{av}\Delta t}{m_{v2}} \qquad \text{(Eq. 67)}$$

where m_{v2} is given by Equation 66.

<u>3 — 9: Mass Balance over Vapor in Vault</u>

Although the quantity E_{av} represents the rate of evaporation of ammonia from the liquid surface <u>to the air inside the vault</u>, this does <u>not</u> represent the rate of ammonia displaced upward through the drains, because the evaporated ammonia is diluted in the air in the vault, which initially does not contain ammonia.

At the start of the time-step, the vapor volume available in the vault V_{v1} is equal to the total vault volume less the volume occupied by the liquid:

$$V_{v1} = L_v W_v H_v - \frac{m_{v1}}{\rho_{v1}} \qquad \text{(Eq. 68)}$$

where ρ_{v1} is the density of the liquid in the vault at the start of the time step. Similarly, at the end of the time-step, the vapor volume available in the vault V_{v2} is:

$$V_{v2} = L_v W_v H_v - \frac{m_{v2}}{\rho_{v2}} \qquad \text{(Eq. 69)}$$

The total number of kg-moles of vapor in the vault is calculated from the ideal-gas law:

$$n_{T1} = \frac{P_{atm}V_{v1}}{RT} \qquad \text{(Eq. 70)}$$

where:

P_{atm} = atmospheric pressure, assumed equal to 101,325 Pascals
R = the ideal-gas constant = 8314.4 J/kgmol°K
T = absolute temperature, °K.

At the end of the time-step, the total number of kg-moles of vapor is:

$$n_{T2} = \frac{P_{atm} V_{v2}}{RT} \qquad \text{(Eq. 71)}$$

The total number of moles of ammonia entering the vapor space by evaporation is:

$$n_{ae} = \frac{E_{av} \Delta t}{M_a} \qquad \text{(Eq. 72)}$$

and the number of moles of water entering the vapor space by evaporation is:

$$n_{we} = \frac{E_{wv} \Delta t}{M_w} \qquad \text{(Eq. 73)}$$

The total number of moles leaving the vapor space upward through the drain is therefore equal to the initial moles plus the moles evaporated, less the final moles:

$$n_d = n_{T1} + n_{ae} + n_{we} - n_{T2} = \frac{P_{atm}(V_{v1} - V_{v2})}{RT} + \Delta t \left(\frac{E_{av}}{M_a} + \frac{E_{wv}}{M_w} \right) \qquad \text{(Eq. 74)}$$

Prior to the release (t = 0), it is assumed that the vault is filled with air, and the mole fraction of ammonia in the vapor is zero. As all required values are known for time zero, the values at the end of the first time-step are then calculated, and used as the initial values for the next time-step. Calculation then proceeds step-wise until no further liquid enters the vault.

The final number of moles of ammonia in the vault $n_{T2}y_{a2}$ is equal to the initial number of moles of ammonia in the vault $n_{T1}y_{a1}$, plus the number of moles of ammonia evaporated $E_a\Delta t/M_a$, less the number of moles of ammonia leaving the vault through the drain.

If it is assumed that the vapor in the vault is instantaneously and perfectly mixed, the mole fraction of any component at the drain is equal to its mole fraction anywhere in the vault. If the time-step Δt is short enough, it can be assumed that the <u>time-averaged</u> mole fraction ammonia at the drain over the time-step is equal to the arithmetic average of the mole fractions at the start and end of the time-step. In this case, the number of moles of ammonia leaving the drain is:

$$n_{ad} = \frac{n_d (y_{a1} + y_{a2})}{2} \qquad \text{(Eq. 75)}$$

where n_d is given by Equation 74.

The mass (mole) balance for ammonia then becomes:

$$n_{T2}y_{a2} = n_{T1}y_{a1} + \frac{E_{av}\Delta t}{M_a} - \frac{n_d(y_{a1} + y_{a2})}{2} \qquad \text{(Eq. 76)}$$

For any given time-step, all quantities are known in this equation except the final ammonia mole fraction y_{a2}. Solving for y_{a2} results in:

$$y_{a2} = \frac{y_{a1}\left(n_{T1} - \frac{n_d}{2}\right) + \frac{E_{av}\Delta t}{M_a}}{n_{T2} + \frac{n_d}{2}} \qquad \text{(Eq. 77)}$$

Once y_{a2} is calculated, it can be substituted back into Equation 75 in order to calculate the total moles of ammonia leaving the drain during time-step Δt. This can be converted to a <u>mass rate</u> of escape of ammonia from the drain by multiplying by the molecular weight M_a and dividing by the time-step:

$$E_{ad} = \frac{n_{ad}M_a}{\Delta t} = \frac{n_d M_a(y_{a1} + y_{a2})}{2\Delta t} \qquad \text{(Eq. 78)}$$

This quantity, E_{ad} represents the rate of escape of ammonia from the drains due to air displaced from the vault by the liquid solution. It must be added to the rate of direct evaporation from the sump surface E_a in order to calculate the total emission rate of ammonia.

Table A-3 in Appendix A presents the detailed calculations of the evaporation rate of ammonia in the vault, and the emission rate of ammonia in air displaced upward through one drain by downward flow of liquid through the other drain, as described in Sections 3-7 through 3-9.

3 — 10: Results of Emission Rate Calculations

The calculated evaporation rate of ammonia directly from the liquid surface in the sloping sump remains nearly constant at about 48.5 g/s (0.0485 kg/s) for 140 seconds, until the liquid level reaches the sloping part of the sump. The evaporation rate then declines rapidly to zero after 156.9 seconds of total elapsed time, when the sump is empty.

The calculated emission rate of ammonia in air from the vault displaced upward through the drains rises from zero to a maximum of 6.49 g/s after 146 seconds, then declines to 3.82 g/s after 156.9 seconds of total elapsed time. The total mass of ammonia emitted up-ward through the drains in displaced air is only 539 g, as compared to a total of 7,256 g (7.256 kg, or about 16 lb) evaporated directly from the liquid surface in the sump.

Superposition of the emission from displaced air on direct evaporation from the sump causes the maximum rate to increase from 48.5 g/s to 54.8 g/s.

Figure 3 shows a graph of the calculated ammonia emission rates, in kg/s, as a function of elapsed time in seconds. The dashed line represents direct evaporation from the liquid pool in the sump, while the gray line represents ammonia in air displaced upward from the vault. The thick black line represents the superposition of the two emissions.

The major results of the emission rate calculations are summarized in Table 4 below.

Table 4: Emission Rates for Worst-Case Ammonia Spill

Type of Ammonia Emission→	Pool Evaporation	Ammonia in Displaced Air	Super-position
Total Ammonia Emission, kg	7.256	0.539	7.795
Maximum Emission Rate, kg/s	0.0485	0.0065	0.0548
Emission Duration, s	156.9	156.9	156.9
Average Emission Rate, kg/s	0.0462	0.0034	0.0497
Duration at Maximum Rate, s	149.47	82.98	142.31
Source Radius, m	0.0962	0.0352	0.1021

4 – Release Rate Calculation for Tank Truck Outlet Disconnect

4 – 1: Introduction

The alternative release scenario is the accidental opening of the 3-inch bottom outlet of a tank truck. The tank contains 8,000 gallons of 19.0 wt % aqueous ammonia, which flows into a sloping sump 95'4"x 16 ft. The sump is equipped with a 10-inch drain leading to the same vault that serves the storage tanks.

The aqueous ammonia will not accumulate in the sump because the cross-sectional area of the sump drain is much larger than the cross-sectional area of the bottom outlet of the tank truck. The liquid is assumed to flow in a rectangular "falling film". Although the liquid "sheet" may become narrower as it approaches the drain, the calculations were simplified by conservatively assuming that the falling film covers half the area of the sump, and that ammonia evaporates at a constant rate until the tank truck is empty.

The duration of the emission depends on the time required for the aqueous ammonia to flow through the tank truck bottom outlet, due to the static gravitational pressure of the liquid above the outlet. As the liquid level decreases with time, the flow rate through the outlet also decreases with time. Stepwise mass and energy balances are used to calculate the flow rate as a function of time, and determine the time required to empty the tank.

4 – 2: Tank Truck Dimensions

The tank truck's reservoir was assumed to be a horizontal cylinder 6 feet in diameter and 42 feet long. It was also assumed that the volume of the heads beyond the tangent line (end of the cylindrical section) was negligible.

The volume of the cylindrical portion of the tank is given by:

$$V_c = \pi r^2 L_c = \frac{\pi D^2 L_c}{4} \qquad \text{(Eq. 79)}$$

where:

V_c = cylindrical volume, ft^3
r = tank radius, ft
D = inside tank diameter, ft
L_c = length of cylindrical section, ft

Substituting D = 6 ft and L_c = 42 ft into Equation 79 results in V_c = 1,188 ft^3 = 8,883 gallons (assuming 1 ft^3 = 1728 / 231 gallons). If the tank truck contained 8,000 gallons of solution, it would be 90.06% full by volume.

4 – 3: Liquid Height as a Function of Liquid Volume

The liquid flow rate as a function of time can be obtained using an energy balance similar to Equation 22, which results in an equation for the flow rate similar to Equation 27. In this case, the area of the liquid surface A(z) will be at least $L_c D_d$, while the drain area is constant at $\pi D_d^2/4$, so the maximum value for the area ratio A_d / A(z) would be:

$$\frac{A_d}{A(z)} \leq \frac{\pi D_d^2/4}{L_c D_d} = \frac{\pi D_d}{4L_c} \qquad \text{(Eq. 80)}$$

If it is assumed that the bottom outlet of the tank truck is a 3-inch Schedule 40 pipe, its inside diameter is D_d = 3.068 inches, while L_c = 42 ft = 504 inches. Substituting into Equation 80 gives $A_d/A(z) < 0.00458$, and $[A_d/A(z)]^2 < 2.29(10^{-5})$. This ratio can be neglected compared to unity in the dominator of Equation 27, so the outlet liquid flow rate can be approximated by:

$$Q_d \approx \rho A_d \sqrt{2gz} \qquad \text{(Eq. 81)}$$

It should be noted that the liquid height z will decrease with time, so the outlet flow rate Q_d also decreases with time. In order to perform stepwise mass balances, the relationship must be found between the liquid height and the total liquid volume in a partially-filled horizontal cylinder.

Perry's Chemical Engineers' Handbook (Equation 6-53, page 6-107, Sixth Edition, see Attachment A) gives the following equation for the volume of liquid in a horizontal cylinder of radius r and length L, filled to a height z:

$$V_c = Lr^2(\theta - \sin\theta\cos\theta) \qquad \text{(Eq. 82)}$$

where

$$\cos\theta = 1 - \frac{z}{r} \qquad \text{(Eq. 83)}$$

where the angle θ must be evaluated in radians. As r = D/2, these equations can be re-written as

$$V_c = \frac{L_c D^2}{4}(\theta - \sin\theta\cos\theta) \qquad \text{(Eq. 84)}$$

$$\cos\theta = 1 - \frac{2z}{D} \qquad \text{(Eq. 85)}$$

These equations are valid over the range $0 < z < D$, for which θ varies from 0 to π. It should be noted that for $z > D/2$ (the tank more than half full), $\cos\theta$ is negative, but $\sin\theta$ is positive, so the second term in parentheses in Equation 84 becomes positive, and is added to the total volume.

4 – 4: Stepwise Mass Balance for Tank Truck Release

Prior to the accidental opening of the bottom outlet, the tank truck is assumed to contain exactly 8,000 gallons (= 1069.4 ft^3 = 30.283 m^3) of aqueous ammonia solution at 64°F, the arithmetic mean temperature during 1997. Its density can be calculated using Equation 9, interpolating between 50° and 68°F to get ρ=895.35 kg/m^3. This density remains constant throughout the release because no ammonia evaporates inside the tank.

For the given initial volume, the liquid height z must be found iteratively. A trial value of z is assumed, from which θ is calculated from Equation 85, and the cylindrical volume V_c from Equation 84. If the calculated volume V_c is not within a tolerance of the known liquid volume, z is adjusted using the "Goal Seek" feature under Microsoft Excel.

Once the liquid height is converged, the outlet flow rate is calculated using Equation 81. The final liquid volume at the end of the time step is determined by mass balance (equivalent to a volume balance at constant density):

$$V_2 = V_1 - \frac{Q_d \Delta t}{\rho} = V_1 - A_d \Delta t \sqrt{2 g z_1} \qquad \text{(Eq. 86)}$$

where:

V_1 = initial volume at start of time step
V_2 = final volume at end of time step
A_d = cross-sectional area of tank truck bottom outlet
z_1 = liquid height at start of time-step.

Once the new liquid volume at the end of the time step is obtained, it is assumed to be the initial volume for the next time step, and the liquid height z is converged iteratively using the "Goal Seek" option, as described above. This procedure is repeated until the tank truck is empty ($z = 0$).

These calculations are shown in Table B-1, which extends over 7 pages. The calculations are made for a time step of $\Delta t = 10$ seconds up to 1800 seconds (30 minutes) of simulated time, but shorter time-steps are used thereafter, in order to improve accuracy when the tank is nearly empty. The maximum leak rate through the bottom outlet is 23.5 kg/s, and the release lasts a total of 1864 seconds, or slightly more than 31 minutes. The leak rate as a function of time is plotted as a graph on Figure 4.

5 – Ammonia Evaporation Rate from Falling Film

5 – 1: Introduction

For the alternative release, the leak rate through the 3-inch bottom outlet of the tank truck is assumed to be immediately removed through the 10-inch drain without accumulating in the sloping sump, which is 95'4" long by 16 ft wide.

However, the tank truck bottom outlet may not be located directly over the drain at the time of a hypothetical disconnect, so the spilled solution would have to flow down the gently-sloping sump from the spill point to the drain in a "sheet" of liquid. During the time required for this liquid to travel from the spill point to the drain, ammonia would be evaporating from this "sheet" at a rate given by Equation 31.

The bottom surface of the sump is designed as four triangles, whose boundaries extend from the drain toward each corner of the rectangular edge of the sump (See Figure 1). A liquid spill at a low flow rate would be contained within one of these triangles, but a high-flow spill would tend to overflow the boundaries of a triangle as it narrows down, but then converge toward the drain, whose diameter is large enough to remove this flow rate.

In order to simplify the calculations, it has been assumed that the liquid flows down in a rectangular sheet of constant width from the spill point to the drain, but does not overshoot the drain. Although the area of this sheet would be maximized if the bottom outlet were over the edge of the sump, or 47'8" from the drain, it is more likely that the truck would be parked with some portion of the tank directly over the drain.

In the current alternative scenario, it has been assumed that the truck is parked with one edge of the ammonia tank directly over the drain, such that the distance from the bottom outlet to the drain would be half the length of the tank, or 21 feet. It is therefore assumed that the liquid flows in a rectangular sheet from this point to a parallel line through the drain (See Figure 2). This rectangle would then be 21 feet long by 16 feet wide, having a surface area of $336\ ft^2 = 31.22\ m^2$.

5 – 2: Evaporation Rate from Falling Film

As the liquid film flows across the sump from its impact point below the tank truck bottom outlet toward the drain, some ammonia will evaporate out due to the action of the wind on the film. Theoretically, the solution will be progressively depleted of ammonia, thereby lowering the partial pressure of ammonia above the solution, so the evaporation rate should decrease with distance from the edge of the sump toward the drain.

When the solution leaving the tank truck first hits the sump surface, its ammonia content is 19 wt % (w = 19.0), and the partial pressures can be evaluated using Equations 7 and 8 to be 157.82 mmHg for ammonia and 11.94 mmHg for water, respectively. Inserting these values into Equation 31 and 32 (for a wind speed of 2.5 m/s) results in evaporation rates of 2.07 g/s-m^2 of ammonia and 0.162 g/s-m^2 of water. These calculations are shown in Table B-2, except that evaporation rates are shown in kilograms per second per square meter.

If these evaporation rates are assumed valid over half the area of the sump (neglecting the change in partial pressures with distance), the total evaporation rate would be 146.4 g/s of ammonia and 11.50 g/s of water.

At the initial spill rate of 23.5 kg/s of 19 wt% solution, ammonia enters the sump at a rate of (23.5)(0.19) = 4.465 kg/s, but only 0.146 kg/s evaporates. At the start of the spill, only about 3.3% of the spilled ammonia evaporates, while the rest flows into the drain. This means that the ammonia fraction (and the partial pressure of ammonia) does not change much with distance, and can be assumed constant without incurring much error.

As time goes on, the spill rate from the tank truck decreases, while the evaporation rate should remain nearly constant, as the film area, wind speed, and temperature remain constant. The fraction of spilled ammonia which evaporates increases with time, but it remains below 10% until the spill rate decreases to about 1.46 kg/s, only about 9 seconds before the tank truck is empty, and evaporation stops.

The evaporation rate of ammonia for the tank truck release is thus assumed constant at 0.146 kg/s for the entire duration of the spill (1864 seconds, or 31.06 minutes). This assumption overestimates the actual evaporation rate because the ammonia content of the film does decrease slightly with distance, yet it has been assumed constant at the initial 19.0 weight percent.

6 – Steady-State Dispersion Modeling and Averaging Time

6 – 1: Transient and Steady-State Modeling with DEGADIS

The DEGADIS atmospheric dispersion model used to determine the endpoint distances can be run in either "steady-state" or "transient" mode.

In "steady-state" mode, the emission is assumed to continue at constant rate for all time, and concentrations are calculated for many downwind distances (including many close to the source) independent of elapsed time since the start of the emission. This option will over-estimate concentrations for short-term emissions, but requires short calculation times.

In "transient" mode, the user enters successive values for emission rate (in kg/s) and "source radius" as a function of elapsed time, with a zero emission rate at the last two times indicating the end of the emission. The user then selects a series of equally-spaced values of elapsed time, for which DEGADIS prints out a series of instantaneous concentrations at downwind distances chosen within the program.

In most cases, "transient" mode is better adapted to modeling short-duration (<1 hour) releases, because the variation of concentration with time is taken into account. Because the DEGADIS output format is difficult to interpret directly, TRC has developed a post-processor called DEGADOSE, which reads DEGADIS output and calculates time-averaged concentrations as a function of distance and averaging time, or endpoint distances to given concentration thresholds for a given averaging time.

This approach works well for downwind distances greater than about 500 meters. Close to the source, DEGADIS in transient mode tends to print out concentrations at distances that are too widely-spaced, forcing the post-processor to interpolate over several orders of magnitude, leading to fluctuating concentrations that are difficult to interpret.

Because concentrations at distances less than 500 meters are of interest, DEGADIS was used in "steady-state" mode to improve accuracy. The results are corrected to account for differences between release duration and averaging time for concentration thresholds.

6 – 2: Concentration and Averaging-Time Thresholds

Endpoint distances for both worst-case and alternative release scenarios were computed for the following combinations of concentration threshold and averaging time:

Table 1: Endpoint Concentration Thresholds and Averaging Times

Threshold	Concentration, ppmv	Averaging Time, min.
Lethal	2000	30
IDLH (Immediately Dangerous to Life and Health)	300	30
ERPG-2 (Emergency Response Planning Guideline Level 2)	200	60
STPEL (Short Term Public Emergency Limit)	75	30

6 – 3: Extrapolation of Toxic Thresholds by Averaging Time

The health effects of inhalation of a toxic gas depend not only on the concentration, but also on the time to which an individual is exposed. Certain concentrations, which cause no lasting health damage if inhaled in a single breath, could be fatal for prolonged exposures over several hours.

In comments to the National Advisory Committee on Acute Exposure Guideline Levels (AEGL), Robert A. Michaels, a Toxicology and Risk Assessment consultant, recom-mended the use of the "Ten Berge Equation" for ammonia. This equation states that combinations of concentration C and exposure time t which obey the equation below have equivalent toxic effects:

$$C^2 t = K \qquad \text{(Eq. 87)}$$

where K is a constant for each toxic threshold level, in units of $(\text{ppmv})^2$-min.

For each toxic threshold in Table 1 above, let

C_t = threshold concentration in ppmv
t_{av} = averaging time for threshold in minutes

The K (dose) parameter for the given threshold would then be given by

$$K_t = C_t^2 t_{av} \qquad \text{(Eq. 88)}$$

When the DEGADIS model is run in "steady-state" mode, it calculates, for each downwind distance, the concentration resulting from a continuous emission at the input rate. However, if the emission really only lasted a period of t_e minutes, the downwind receptors would only be exposed to the output concentration for t_e minutes.

In order to choose an endpoint distance whose toxic effects are equivalent to that of the threshold, an equivalent concentration C_e must be calculated which satisfies Equation 87 for $t=t_e$ and $K = K_t$:

$$C_e^{\,2} t_e = K_t = C_t^2 t_{av} \qquad \text{(Eq. 88)}$$

Solving for C_e results in:

$$C_e = C_t \sqrt{\frac{t_{av}}{t_e}} \qquad \text{(Eq. 89)}$$

If the emission duration t_e is less than the averaging time t_{av}, the equivalent concentration C_e will be greater than the threshold concentration C_t, and occur at a shorter downwind distance.

6 – 4: Equivalent Emission Duration for Variable-Rate Emissions

The DEGADIS model, in steady-state mode, only accepts input of a single emission rate Q. For time-varying release rates (such as those for the worst-case evaporation from the slop-ing sump after instantaneous release of the tank contents), this emission rate was chosen as the maximum (initial) evaporation rate Q_{max}.

However, if t_e were assumed equal to the actual emission duration, the total mass emitted in the model $Q_{max}t_e$ would be greater than the actual mass emitted; since the actual emission rate is less than Q_{max} during part of the emission. The equivalent emission duration was thus adjusted by dividing the total actual mass emitted by the maximum emission rate:

$$t_e = \frac{m_{total}}{Q_{max}} \qquad \text{(Eq. 90)}$$

The total mass emitted was estimated by summing the mass emitted over each time step:

$$m_{tot} = \sum_{i=1}^{N} Q_i \Delta t_i \qquad \text{(Eq. 91)}$$

where N is the number of time steps in the stepwise mass-balance calculation.

6 – 5: Neutral-Buoyancy Modeling and Source Radius

The DEGADIS model allows the user to input "triples"—combinations of mole fraction of pollutant, pollutant concentration in kg/m^3, and density of the pollutant/air mixture in kg/m^3. The ammonia vapor releases were artificially "forced" to become neutrally buoyant by entering the ambient air density for pollutant mole fractions of zero (pure air) and one (pure ammonia). This is a conservative approach, which prevents the model from predicting that the cloud will "lift off" the ground, even though it may actually lift off to some extent.

The DEGADIS model also requires the input of a "source radius" for an emission rate assumed to be Q_{max}. At the elapsed time t_e, when the last "puff" of ammonia is leaving the source, the first "puff" would have been carried downwind a distance ut_e, where u is the wind speed. The overall emission can be assumed to be a horizontal cylinder whose total mass is $Q_{max}t_e$ and whose length is ut_e. If its density is assumed equal to that of air (ρ_a), the radius r_s of this cylinder can be calculated by equating the volume times the density to the total mass:

$$\rho_a \pi r_s^2 u t_e = Q_{max} t_e \qquad \text{(Eq. 92)}$$

from which:

$$r_s = \sqrt{\frac{Q_{max}}{\pi \rho_a u}} \qquad \text{(Eq. 93)}$$

The DEGADIS steady-state simulation is set up using an emission rate of Q_{max} and a source radius calculated from Equation 93.

Once the output is obtained, the equivalent emission duration is obtained from Equation 90 (where m_{tot} is obtained from the stepwise mass balances using Equation 91). For each concentration threshold in Table 1, an equivalent concentration C_e is obtained for the corrected emission duration using Equation 89.

6 – 6: Interpolation of Endpoint Distances

In steady-state mode, the DEGADIS model prints out a series of downwind distances X_I and corresponding concentrations C_I, but it is rare that a concentration is printed out exactly equal to the target concentration C_e.

If the target concentration C_e does not appear in the output, the two closest concentrations C_1 and C_2 are selected which "straddle" the target concentration C_e, such that

$$C_1 < C_e < C_2$$

Let X_1 and X_2 be the downwind distances corresponding to concentrations C_1 and C_2, respectively. It is then assumed that, between these distances, concentration varies with downwind distance according to a power-law equation:

$$C = aX^{-b} \qquad \text{(Eq. 94)}$$

where a and b are constants. If this is valid for both X_1 and X_2, then

$$C_1 = aX_1^{-b} \qquad \text{(Eq. 95)}$$

and

$$C_2 = aX_2^{-b} \qquad \text{(Eq. 96)}$$

Equations 95 and 96 can be solved together for the two unknown parameters a and b. Once they are known, a downwind distance X_e can be obtained for which

$$C_e = aX_e^{-b} \qquad \text{(Eq. 97)}$$

which is the endpoint distance for the concentration C_e. Combining Equations 95, 96, and 97 and solving for X_e results in:

$$X_e = X_1 \exp\left[\frac{\ln\left(X_2/X_1\right)\ln\left(C_e/C_1\right)}{\ln\left(C_2/C_1\right)}\right] \qquad \text{(Eq. 98)}$$

This "log-log interpolation" technique is used to calculate the endpoint distances for the four concentration thresholds.

6 – 7: Summary of DEGADIS Output Results

Table C-1 presents the output results for the worst-case release scenario, and Table C-2 presents the output data for the alternative release scenario.

The top five lines of Table C-1 present the following information:

Total Mass Ammonia Emitted (m_{tot} in Equation 91)
Maximum Emission Rate (Q_{max})
Actual Emission Duration
Average Emission Rate
Equivalent Duration at Maximum Rate (t_e in Equations 89 and 90)

The last four lines of each table correspond to the four toxic thresholds given in Table 1. The first three columns repeat the information given in Table 1. The remaining columns contain the following information, for each toxic threshold:

Column 4: C^2t = K parameter from Equation 87

Column 5: Equivalent Concentration at Duration: C_e from Equation 89

Columns 6-7: Straddling Distances X_1 and X_2 from DEGADIS output corresponding to concentrations immediately above and below C_e

Columns 8-9: Straddling Concentrations C_1 and C_2 from DEGADIS output

Column 10: Endpoint distance: X_e from Equation 98 in meters

Column 11: Endpoint distance X_e converted to miles.

Table A-1:
24,000-Gallon Aqueous Ammonia Spill into 52x24 ft Sloping Sump:
Initial Liquid Height Calculation

Sump Length at Top	52	ft
	15.8496	m
Sump Width at Top	24	ft
	7.3152	m
Drain Radius	12	inch
	0.3048	m
Minimum Slope	72	Reciprocal
	0.01389	Up/out
Sump Depth	0.1058	m
	4.17	inch
Length as function of Height		
Intercept	0.610	m
Coefficient	144.00	m/m
Width as Function of Height		
Intercept	0.610	m
Coefficient	63.36	m/m
Total Volume of 1 Sloping Sump	4.352	m^3
	153.70	ft^3
	1,150	gallons
Volume of Initial Spill	24,000	gallons
	3,208.33	ft^3
	90.850	m^3
Initial Volume Above Sloping Sump	86.497	m^3
Area Above Sloping Sump	115.94	m^2
Liquid Height Above Sloping Sump	0.7460	m
	29.37	inch
Total Initial Liquid Height	0.8519	m
	33.54	inch

Table A-2: Release Rates as a Function of Time for 19% Aqueous Ammonia Spill:
24,000-Gallon Instantaneous Spill into 52'x24' Sump with 24" Drain, Close-Packed Balls, 1.5 m/s Wind

Volume Spilled	24,000	gal	Number of Sumps	1		Density Function:		10 C	20 C	43.89 C
	90.85	m^3	Sump Length at Top	52	ft	$\rho = a + bx + cx^2$	a	0.99931	0.99785	0.99436
Initial Wt. % Ammonia	19	wt %		15.8496	m	ρ in g/cm³	b	-4.099E-3	-4.249E-3	-4.606E-3
Initial Mol % Ammonia	19.88	mol %	Sump Width at Top	24	ft	x in wt% NH_3	c	2.476E-5	2.431E-5	2.325E-5
Initial Density	915.25	kg/m^3		7.3152	m	Vapor Pressure Function:		NH_3	H_2O	
Drain Diameter	24	inch	Length as function of Height			$P = a + by + cy^2 + dy^3$	a	0.00000	67.6516	
	0.6096	m	Intercept	0.610	m	P in mmHg	b	23.74516	-0.7211	
Grating Mesh Size	1.000	inch	Coefficient	144.00	m/m	y in mol% NH_3	c	-0.70329	0.0000	
Grating Wire Size	0.125	inch	Width as Function of Height				d	0.04623	0.0000	
Area of All Drains	0.2189	m^2	Intercept	0.610	m	Molecular Weight, g/gmol		17.03	18.016	
Sump Depth	0.1058	m	Coefficient	63.36	m/m	Ambient Temperature		111.00 °F		
	4.17	inch	Acceleration of Gravity	9.80665	m/s^2			43.89 °C		
Volume of 1 Sloping Sump	4.352	m^3	Balls Area Void Fraction	0.09310				317.04 °K		
Volume of All Sloping Sumps	4.352	m^3	Wind Speed	1.50	m/s					

Time, sec	Initial Volume, m³	Liquid Height, m	Initial Mass, kg NH_3	Initial Mass, kg H_2O	Liquid Surface Length, m	Liquid Surface Width, m	Evap. Area, m²	Calculated Volume, m³ Sloping	Calculated Volume, m³ Straight	Calculated Volume, m³ Total	Calculated Volume, m³ Error	Drain Rate m/s	Drain Rate m³/s	Drain Rate kg/s	Mass Drained, kg NH_3	Mass Drained, kg H_2O	Mass Before Evap, kg NH_3	Mass Before Evap, kg H_2O	Mol % NH_3	Mass % NH_3	Density, kg/m³	Partial Pressure, mmHg NH_3	Partial Pressure, mmHg H_2O	Evap. Rate, kg/s NH_3	Evap. Rate, kg/s H_2O	Source Radius, m
0	90.850	0.8519	15,798.49	67,351.46	15.850	7.315	10.794	4.352	86.497	90.850	0.00000	4.0884	0.89494	819.086	778.13	3,317.30	15,020	64,034	19.88	19.00	915.25	557.41	53.95	0.0485	0.0049	0.0951
5	86.375	0.8133	15,020.31	64,034.15	15.850	7.315	10.794	4.352	82.023	86.375	0.00000	3.9947	0.87443	800.316	760.30	3,241.28	14,260	60,793	19.88	19.00	915.25	557.41	53.95	0.0485	0.0049	0.0951
10	82.003	0.7756	14,259.77	60,792.85	15.850	7.315	10.794	4.352	77.650	82.003	0.00000	3.9010	0.85391	781.541	742.45	3,165.25	13,517	57,628	19.88	19.00	915.25	557.39	53.95	0.0485	0.0049	0.0951
15	77.733	0.7387	13,517.07	57,627.57	15.850	7.315	10.794	4.352	73.380	77.733	0.00000	3.8072	0.83339	762.760	724.60	3,089.20	12,792	54,538	19.88	19.00	915.25	557.38	53.95	0.0485	0.0049	0.0951
20	73.565	0.7028	12,792.23	54,538.34	15.850	7.315	10.794	4.352	69.213	73.565	0.00000	3.7134	0.81287	743.974	706.74	3,013.13	12,085	51,525	19.88	19.00	915.25	557.36	53.95	0.0485	0.0049	0.0951
25	69.501	0.6677	12,085.24	51,525.19	15.850	7.315	10.794	4.352	65.148	69.501	0.00000	3.6196	0.79233	725.181	688.88	2,937.03	11,396	48,588	19.88	19.00	915.25	557.35	53.95	0.0485	0.0049	0.0951
30	65.539	0.6336	11,396.12	48,588.14	15.850	7.315	10.794	4.352	61.186	65.539	0.00000	3.5258	0.77179	706.382	671.01	2,860.90	10,725	45,727	19.88	19.00	915.25	557.33	53.95	0.0485	0.0049	0.0951
35	61.679	0.6003	10,724.87	45,727.22	15.850	7.315	10.794	4.352	57.327	61.679	0.00000	3.4319	0.75124	687.577	653.14	2,784.75	10,072	42,942	19.88	19.00	915.25	557.31	53.95	0.0485	0.0049	0.0951
40	57.923	0.5679	10,071.49	42,942.45	15.850	7.315	10.794	4.352	53.570	57.923	0.00000	3.3380	0.73069	668.764	635.25	2,708.57	9,436	40,234	19.88	19.00	915.25	557.29	53.95	0.0485	0.0049	0.0951
45	54.269	0.5364	9,436.00	40,233.86	15.850	7.315	10.794	4.352	49.916	54.269	0.00000	3.2441	0.71012	649.944	617.36	2,632.36	8,819	37,602	19.88	19.00	915.26	557.27	53.95	0.0485	0.0049	0.0951
50	50.718	0.5057	8,818.39	37,601.48	15.850	7.315	10.794	4.352	46.365	50.718	0.00000	3.1501	0.68955	631.116	599.47	2,556.11	8,219	35,045	19.88	19.00	915.26	557.25	53.95	0.0485	0.0049	0.0951
55	47.270	0.4760	8,218.68	35,045.34	15.850	7.315	10.794	4.352	42.917	47.270	0.00000	3.0561	0.66897	612.279	581.56	2,479.83	7,637	32,566	19.88	19.00	915.26	557.23	53.95	0.0485	0.0049	0.0951
60	43.925	0.4471	7,636.88	32,565.48	15.850	7.315	10.794	4.352	39.572	43.925	0.00000	2.9620	0.64838	593.433	563.65	2,403.52	7,073	30,162	19.88	19.00	915.26	557.20	53.95	0.0485	0.0049	0.0951
65	40.682	0.4192	7,072.99	30,161.94	15.850	7.315	10.794	4.352	36.330	40.682	0.00000	2.8679	0.62777	574.578	545.72	2,327.17	6,527	27,835	19.88	19.00	915.26	557.18	53.95	0.0485	0.0049	0.0951
70	37.543	0.3921	6,527.03	27,834.74	15.850	7.315	10.794	4.352	33.191	37.543	0.00000	2.7737	0.60716	555.713	527.79	2,250.78	5,999	25,584	19.88	19.00	915.26	557.15	53.95	0.0485	0.0049	0.0951
75	34.507	0.3659	5,998.99	25,583.94	15.850	7.315	10.794	4.352	30.154	34.507	0.00000	2.6795	0.58654	536.837	509.84	2,174.34	5,489	23,410	19.88	18.99	915.27	557.12	53.95	0.0485	0.0049	0.0951
80	31.574	0.3406	5,488.91	23,409.58	15.850	7.315	10.794	4.352	27.221	31.574	0.00000	2.5852	0.56590	517.949	491.89	2,097.85	4,997	21,312	19.87	18.99	915.27	557.08	53.96	0.0485	0.0049	0.0951
85	28.744	0.3162	4,996.77	21,311.70	15.850	7.315	10.794	4.352	24.392	28.744	0.00000	2.4909	0.54525	499.048	473.92	2,021.32	4,523	19,290	19.87	18.99	915.27	557.04	53.96	0.0485	0.0049	0.0951
90	26.017	0.2927	4,522.61	19,290.36	15.850	7.315	10.794	4.352	21.665	26.017	0.00000	2.3965	0.52458	480.134	455.94	1,944.73	4,067	17,346	19.87	18.99	915.27	557.00	53.96	0.0485	0.0049	0.0951
95	23.394	0.2701	4,066.43	17,345.61	15.850	7.315	10.794	4.352	19.042	23.394	0.00000	2.3020	0.50390	461.205	437.94	1,868.08	3,628	15,478	19.87	18.99	915.28	556.95	53.96	0.0485	0.0049	0.0951
100	20.874	0.2483	3,628.24	15,477.50	15.850	7.315	10.794	4.352	16.522	20.874	0.00000	2.2074	0.48319	442.259	419.93	1,791.36	3,208	13,686	19.87	18.99	915.28	556.90	53.96	0.0485	0.0049	0.0951
105	18.458	0.2275	3,208.07	13,686.11	15.850	7.315	10.794	4.352	14.105	18.458	0.00000	2.1127	0.46248	423.297	401.90	1,714.58	2,806	11,972	19.87	18.99	915.29	556.84	53.96	0.0485	0.0049	0.0951
110	16.145	0.2075	2,805.92	11,971.51	15.850	7.315	10.794	4.352	11.793	16.145	0.00000	2.0180	0.44173	404.315	383.85	1,637.72	2,422	10,334	19.87	18.99	915.29	556.77	53.96	0.0485	0.0049	0.0950
115	13.936	0.1885	2,421.82	10,333.76	15.850	7.315	10.794	4.352	9.584	13.936	0.00000	1.9231	0.42097	385.312	365.78	1,560.78	2,056	8,773	19.87	18.99	915.30	556.70	53.96	0.0485	0.0049	0.0950
120	11.831	0.1703	2,055.80	8,772.96	15.850	7.315	10.794	4.352	7.478	11.831	0.00000	1.8282	0.40018	366.287	347.69	1,483.74	1,708	7,289	19.87	18.98	915.30	556.60	53.96	0.0485	0.0049	0.0950
125	9.830	0.1531	1,707.86	7,289.19	15.850	7.315	10.794	4.352	5.477	9.830	0.00000	1.7331	0.37936	347.235	329.57	1,406.61	1,378	5,883	19.86	18.98	915.31	556.49	53.96	0.0485	0.0049	0.0950
130	7.932	0.1367	1,378.05	5,882.56	15.850	7.315	10.794	4.352	3.580	7.932	0.00000	1.6378	0.35851	328.155	311.42	1,329.36	1,067	4,553	19.86	18.98	915.32	556.35	53.97	0.0485	0.0049	0.0950
135	6.139	0.1212	1,066.39	4,553.18	15.850	7.315	10.794	4.352	1.787	6.139	0.00000	1.5424	0.33763	309.043	58.65	250.40	1,008	4,303	19.86	18.98	915.33	556.18	53.97	0.0484	0.0049	0.0950

Table A-2: Release Rates as a Function of Time for 19% Aqueous Ammonia Spill:
24,000-Gallon Instantaneous Spill into 52'x24' Sump with 24" Drain, Close-Packed Balls, 1.5 m/s Wind

Volume Spilled	24,000	gal
	90.85	m^3
Initial Wt. % Ammonia	19	wt %
Initial Mol % Ammonia	19.88	mol %
Initial Density	915.25	kg/m^3
Drain Diameter	24	inch
	0.6096	m
Grating Mesh Size	1.000	inch
Grating Wire Size	0.125	inch
Area of All Drains	0.2189	m^2
Sump Depth	0.1058	m
	4.17	inch
Volume of 1 Sloping Sump	4.352	m^3
Volume of All Sloping Sumps	4.352	m^3

Number of Sumps	1	
Sump Length at Top	52	ft
	15.8496	m
Sump Width at Top	24	ft
	7.3152	m
Length as function of Height		
Intercept	0.610	m
Coefficient	144.00	m/m
Width as Function of Height		
Intercept	0.610	m
Coefficient	63.36	m/m
Acceleration of Gravity	9.80665	m/s^2
Balls Area Void Fraction	0.09310	
Wind Speed	1.50	m/s

Density Function:		10 C	20 C	43.89 C
$\rho = a + bx + cx^2$	a	0.99931	0.99785	0.99436
ρ in g/cm^3	b	-4.099E-3	-4.249E-3	-4.606E-3
x in wt% NH_3	c	2.476E-5	2.431E-5	2.325E-5
Vapor Pressure Function:		NH_3	H_2O	
$P = a + by + cy^2 + dy^3$	a	0.00000	67.6516	
P in mmHg	b	23.74516	-0.7211	
y in mol% NH_3	c	-0.70329	0.0000	
	d	0.04623	0.0000	
Molecular Weight, g/gmol		17.03	18.016	
Ambient Temperature		111.00 °F		
		43.89 °C		
		317.04 °K		

Time, sec	Initial Volume, m^3	Liquid Height, m	Initial Mass, kg NH_3	Initial Mass, kg H_2O	Liquid Surface Length, m	Liquid Surface Width, m	Evap. Area, m^2	Calculated Volume, m^3 Sloping	Calculated Volume, m^3 Straight	Calculated Volume, m^3 Total	Calculated Volume, m^3 Error	Drain Rate m/s	Drain Rate m^3/s	Drain Rate kg/s	Mass Drained, kg NH_3	Mass Drained, kg H_2O	Mass Before Evap, kg NH_3	Mass Before Evap, kg H_2O	Mol % NH_3	Mass % NH_3	Density, kg/m^3	Partial Pressure, mmHg NH_3	Partial Pressure, mmHg H_2O	Evap. Rate, kg/s NH_3	Evap. Rate, kg/s H_2O	Source Radius, m
136	5.802	0.1183	1,007.70	4,302.78	15.850	7.315	10.794	4.352	1.449	5.802	0.00000	1.5238	0.33355	305.309	57.93	247.37	950	4,055	19.86	18.98	915.34	556.14	53.97	0.0484	0.0049	0.0950
137	5.468	0.1155	949.72	4,055.40	15.850	7.315	10.794	4.352	1.116	5.468	0.00000	1.5051	0.32947	301.575	57.22	244.35	892	3,811	19.86	18.97	915.34	556.10	53.97	0.0484	0.0049	0.0950
138	5.139	0.1126	892.45	3,811.04	15.850	7.315	10.794	4.352	0.786	5.139	0.00000	1.4865	0.32539	297.841	56.51	241.33	836	3,570	19.85	18.97	915.34	556.05	53.97	0.0484	0.0049	0.0950
139	4.813	0.1098	835.88	3,569.71	15.850	7.315	10.794	4.352	0.461	4.813	0.00000	1.4678	0.32131	294.106	55.80	238.30	780	3,331	19.85	18.97	915.35	556.01	53.97	0.0484	0.0049	0.0950
140	4.492	0.1070	780.03	3,331.40	15.850	7.315	10.794	4.352	0.139	4.492	0.00000	1.4492	0.31723	290.371	55.09	235.28	725	3,096	19.85	18.97	915.35	555.96	53.97	0.0484	0.0049	0.0950
141	4.174	0.1043	724.90	3,096.11	15.625	7.217	10.498	4.174	0.000	4.174	0.00000	1.4304	0.31311	286.610	54.37	232.24	671	2,864	19.85	18.97	915.35	555.91	53.97	0.0471	0.0047	0.0937
142	3.861	0.1014	670.48	2,863.87	15.215	7.036	9.967	3.861	0.000	3.861	0.00000	1.4108	0.30881	282.675	53.62	229.05	617	2,635	19.85	18.97	915.36	555.85	53.97	0.0447	0.0045	0.0913
143	3.552	0.0985	616.81	2,634.82	14.788	6.848	9.428	3.552	0.000	3.552	0.00000	1.3900	0.30427	278.520	52.83	225.69	564	2,409	19.85	18.97	915.36	555.80	53.97	0.0423	0.0043	0.0887
144	3.248	0.0954	563.93	2,409.13	14.342	6.652	8.882	3.248	0.000	3.248	0.00000	1.3681	0.29946	274.118	51.99	222.12	512	2,187	19.85	18.97	915.36	555.74	53.97	0.0398	0.0040	0.0861
145	2.948	0.0921	511.90	2,187.00	13.875	6.447	8.328	2.948	0.000	2.948	0.00000	1.3447	0.29434	269.432	51.10	218.33	461	1,969	19.85	18.97	915.37	555.68	53.97	0.0373	0.0038	0.0834
146	2.654	0.0887	460.76	1,968.67	13.385	6.231	7.764	2.654	0.000	2.654	0.00000	1.3196	0.28886	264.417	50.15	214.27	411	1,754	19.85	18.97	915.37	555.61	53.98	0.0348	0.0035	0.0805
147	2.365	0.0851	410.57	1,754.39	12.867	6.003	7.191	2.365	0.000	2.365	0.00000	1.2927	0.28296	259.018	49.12	209.90	361	1,544	19.84	18.96	915.38	555.55	53.98	0.0322	0.0033	0.0775
148	2.082	0.0813	361.42	1,544.49	12.316	5.761	6.606	2.082	0.000	2.082	0.00000	1.2634	0.27656	253.161	48.01	205.15	313	1,339	19.84	18.96	915.38	555.48	53.98	0.0296	0.0030	0.0743
149	1.805	0.0772	313.38	1,339.34	11.728	5.502	6.007	1.805	0.000	1.805	0.00000	1.2314	0.26956	246.749	46.79	199.96	267	1,139	19.84	18.96	915.39	555.40	53.98	0.0269	0.0027	0.0708
150	1.536	0.0728	266.57	1,139.37	11.094	5.223	5.394	1.536	0.000	1.536	0.00000	1.1960	0.26180	239.647	45.44	194.21	221	945	19.84	18.96	915.39	555.32	53.98	0.0242	0.0024	0.0671
151	1.274	0.0680	221.11	945.16	10.402	4.918	4.763	1.274	0.000	1.274	0.00000	1.1561	0.25307	231.663	43.92	187.74	177	757	19.84	18.96	915.40	555.24	53.98	0.0213	0.0022	0.0631
152	1.021	0.0627	177.17	757.41	9.637	4.582	4.111	1.021	0.000	1.021	0.00000	1.1104	0.24307	222.507	42.18	180.33	135	577	19.84	18.96	915.41	555.14	53.98	0.0184	0.0019	0.0586
153	0.778	0.0567	134.97	577.09	8.771	4.201	3.430	0.778	0.000	0.778	0.00000	1.0565	0.23127	211.704	40.13	171.58	95	406	19.83	18.95	915.41	555.04	53.98	0.0154	0.0016	0.0535
154	0.547	0.0497	94.82	405.51	7.760	3.756	2.713	0.547	0.000	0.547	0.00000	0.9901	0.21672	198.393	37.60	160.79	57	245	19.83	18.95	915.42	554.91	53.99	0.0121	0.0012	0.0476
155	0.330	0.0409	57.21	244.71	6.505	3.203	1.940	0.330	0.000	0.330	0.00000	0.9018	0.19741	180.715	3.42	14.65	54	230	19.83	18.95	915.44	554.74	53.99	0.0087	0.0009	0.0402
155.1	0.310	0.0400	53.79	230.07	6.366	3.142	1.862	0.310	0.000	0.310	0.00000	0.8916	0.19517	178.667	3.39	14.48	50	216	19.83	18.95	915.44	554.73	53.99	0.0083	0.0008	0.0394
155.2	0.291	0.0390	50.40	215.58	6.222	3.079	1.784	0.291	0.000	0.291	0.00000	0.8810	0.19284	176.537	3.35	14.31	47	201	19.83	18.95	915.44	554.72	53.99	0.0080	0.0008	0.0386
155.3	0.271	0.0379	47.05	201.28	6.074	3.014	1.704	0.271	0.000	0.271	0.00000	0.8699	0.19042	174.316	3.30	14.13	44	187	19.83	18.95	915.44	554.71	53.99	0.0076	0.0008	0.0377
155.4	0.252	0.0369	43.75	187.15	5.920	2.946	1.624	0.252	0.000	0.252	0.00000	0.8583	0.18789	171.998	3.26	13.94	40	173	19.83	18.95	915.44	554.69	53.99	0.0073	0.0007	0.0368
155.5	0.233	0.0358	40.49	173.21	5.761	2.876	1.543	0.233	0.000	0.233	0.00000	0.8462	0.18524	169.572	3.21	13.74	37	159	19.83	18.95	915.44	554.68	53.99	0.0069	0.0007	0.0359
155.6	0.215	0.0346	37.28	159.46	5.596	2.804	1.461	0.215	0.000	0.215	0.00000	0.8335	0.18245	167.026	3.16	13.54	34	146	19.83	18.95	915.44	554.66	53.99	0.0065	0.0007	0.0349
155.7	0.197	0.0334	34.11	145.92	5.423	2.728	1.377	0.197	0.000	0.197	0.00000	0.8202	0.17953	164.349	3.11	13.32	31	133	19.83	18.95	915.44	554.65	53.99	0.0062	0.0006	0.0339
155.8	0.179	0.0322	31.00	132.60	5.243	2.648	1.293	0.179	0.000	0.179	0.00000	0.8061	0.17644	161.524	3.06	13.09	28	120	19.83	18.95	915.44	554.63	53.99	0.0058	0.0006	0.0328
155.9	0.161	0.0309	27.94	119.51	5.054	2.565	1.207	0.161	0.000	0.161	0.00000	0.7911	0.17318	158.535	3.00	12.85	25	107	19.83	18.95	915.44	554.62	53.99	0.0054	0.0005	0.0317
156.0	0.144	0.0295	24.93	106.66	4.854	2.477	1.119	0.144	0.000	0.144	0.00000	0.7753	0.16971	155.362	2.94	12.59	22	94	19.83	18.95	915.45	554.60	53.99	0.0050	0.0005	0.0305
156.1	0.127	0.0280	21.99	94.07	4.642	2.384	1.030	0.127	0.000	0.127	0.00000	0.7584	0.16602	151.984	2.88	12.32	19	82	19.83	18.95	915.45	554.58	53.99	0.0046	0.0005	0.0293
156.2	0.110	0.0264	19.11	81.75	4.416	2.285	0.939	0.110	0.000	0.110	0.00000	0.7404	0.16208	148.377	2.81	12.03	16	70	19.82	18.95	915.45	554.56	53.99	0.0042	0.0004	0.0280
156.3	0.094	0.0247	16.30	69.72	4.173	2.177	0.846	0.094	0.000	0.094	0.00000	0.7212	0.15787	144.523	2.74	11.71	14	58	19.82	18.95	915.45	554.54	53.99	0.0038	0.0004	0.0266
156.4	0.078	0.0229	13.56	58.01	3.907	2.061	0.750	0.078	0.000	0.078	0.00000	0.7007	0.15339	140.420	2.66	11.38	11	47	19.82	18.94	915.45	554.52	53.99	0.0034	0.0003	0.0250
156.5	0.063	0.0209	10.90	46.63	3.613	1.931	0.650	0.063	0.000	0.063	0.00000	0.6793	0.14870	136.130	5.16	22.07	6	25	19.82	18.94	915.45	554.50	53.99	0.0029	0.0003	0.0233
156.7	0.033	0.0157	5.74	24.56	2.868	1.603	0.428	0.033	0.000	0.033	0.00000	0.6454	0.14127	129.326	2.45	10.48	3	14	19.82	18.94	915.46	554.42	53.99	0.0019	0.0002	0.0189
156.8	0.019	0.0120	3.29	14.08	2.345	1.373	0.300	0.019	0.000	0.019	0.00000	0.7117	0.15580	142.627	2.70	11.56	1	3	19.82	18.94	915.46	554.37	53.99	0.0013	0.0001	0.0158
156.9	0.003	0.0046	0.59	2.51	1.278	0.904	0.108	0.003	0.000	0.003	0.00000	#NUM!	#NUM!	#NUM!	#NUM!	#NUM!	#NUM!	#NUM!	19.82	18.94	915.47	554.19	54.00	0.0005	0.0000	0.0095

Table A-3: Ammonia Emission Rates from Drains in Air Displaced from Vault:
30,000-Gallon Instantaneous Spill into 60'x30' Sump with 24" Drain, Close-Packed Balls, 1.5 m/s Wind

Time,	Drain Rate			Mass Drained, kg		Cumul In Vault, kg		Mol %	Mass %	Density	Partial Pressure, mmHg		Volume in Vault, m³		Height in Vault, m		Evaporation Rate, kg/s		Initial kgmol in Airspace				Mole Fraction in Airspace			Vapor Out thru Drain			Cumul kg
sec	m/s	m³/s	kg/s	NH_3	H_2O	NH_3	H_2O	NH_3	NH_3	kg/m³	NH_3	H_2O	Solution	Air Space	Solution	Air Space	NH_3	H_2O	NH_3	H_2O	Air	Total	NH_3	H_2O	Air	Total kmol	kmol NH_3	kg/s NH_3	NH_3
0	4.0884	0.89494	819.086	778.13	3,317.30	0.00	0.00	19.88	19.00	915.25	557.41	53.95	0.000	106.562	0.0000	1.8288	0.004596	0.000462	0.00000	0.20379	3.89236	4.09615	0.000000	0.049751	0.950249	0.17348	0.000029	0.000099	0.000497
5	3.9947	0.87443	800.316	760.30	3,241.28	778.11	3,317.30	19.88	19.00	915.25	557.39	53.95	4.475	102.087	0.0768	1.7520	0.004667	0.000469	0.00132	0.19528	3.72754	3.92414	0.000336	0.049765	0.949899	0.16956	0.000087	0.000297	0.001983
10	3.9010	0.85391	781.541	742.45	3,165.25	1,538.38	6,558.58	19.88	19.00	915.25	557.38	53.95	8.847	97.715	0.1518	1.6770	0.004740	0.000476	0.00260	0.18697	3.56651	3.75608	0.000693	0.049779	0.949528	0.16564	0.000146	0.000498	0.004472
15	3.8072	0.83339	762.760	724.60	3,089.20	2,280.81	9,723.83	19.88	19.00	915.25	557.38	53.95	13.116	93.446	0.2251	1.6037	0.004816	0.000484	0.00385	0.17886	3.40926	3.59197	0.001071	0.049794	0.949134	0.16172	0.000206	0.000701	0.007977
20	3.7134	0.81287	743.974	706.74	3,013.13	3,005.39	12,813.03	19.88	19.00	915.25	557.37	53.95	17.283	89.279	0.2966	1.5322	0.004894	0.000492	0.00506	0.17094	3.25580	3.43179	0.001474	0.049811	0.948716	0.15780	0.000266	0.000907	0.012511
25	3.6196	0.79233	725.181	688.88	2,937.03	3,712.11	15,826.15	19.88	19.00	915.25	557.37	53.95	21.347	85.214	0.3664	1.4624	0.004975	0.000500	0.00623	0.16321	3.10612	3.27557	0.001901	0.049828	0.948271	0.15388	0.000328	0.001116	0.018091
30	3.5258	0.77179	706.382	671.01	2,860.90	4,400.96	18,763.17	19.88	19.00	915.25	557.36	53.95	25.309	81.253	0.4344	1.3944	0.005059	0.000508	0.00736	0.15568	2.96024	3.12329	0.002357	0.049846	0.947797	0.14996	0.000390	0.001328	0.024729
35	3.4319	0.75124	687.577	653.14	2,784.75	5,071.95	21,624.07	19.88	19.00	915.25	557.35	53.95	29.168	77.394	0.5006	1.3282	0.005145	0.000517	0.00846	0.14835	2.81815	2.97495	0.002842	0.049866	0.947291	0.14604	0.000453	0.001543	0.032444
40	3.3380	0.73069	668.764	635.25	2,708.57	5,725.06	24,408.81	19.88	19.00	915.25	557.34	53.95	32.924	73.638	0.5650	1.2638	0.005234	0.000526	0.00951	0.14121	2.67985	2.83057	0.003361	0.049887	0.946752	0.14212	0.000517	0.001761	0.041249
45	3.2441	0.71012	649.944	617.36	2,632.36	6,360.28	27,117.38	19.88	19.00	915.25	557.33	53.95	36.578	69.984	0.6277	1.2011	0.005326	0.000535	0.01053	0.13426	2.54534	2.69014	0.003916	0.049910	0.946175	0.13819	0.000582	0.001983	0.051163
50	3.1501	0.68955	631.116	599.47	2,556.11	6,977.62	29,749.73	19.88	19.00	915.25	557.33	53.95	40.128	66.434	0.6887	1.1401	0.005421	0.000545	0.01151	0.12751	2.41463	2.55366	0.004509	0.049934	0.945557	0.13427	0.000648	0.002208	0.062201
55	3.0561	0.66897	612.279	581.56	2,479.83	7,577.06	32,305.84	19.88	19.00	915.25	557.32	53.95	43.576	62.986	0.7478	1.0810	0.005519	0.000555	0.01246	0.12096	2.28771	2.42113	0.005146	0.049959	0.944895	0.13035	0.000715	0.002436	0.074382
60	2.9620	0.64838	593.433	563.65	2,403.52	8,158.59	34,785.67	19.88	19.00	915.25	557.31	53.95	46.921	59.641	0.8052	1.0236	0.005620	0.000565	0.01336	0.11460	2.16460	2.29256	0.005829	0.049987	0.944184	0.12642	0.000783	0.002668	0.087722
65	2.8679	0.62777	574.578	545.72	2,327.17	8,722.21	37,189.19	19.88	19.00	915.25	557.30	53.95	50.163	56.399	0.8609	0.9679	0.005724	0.000575	0.01423	0.10843	2.04528	2.16794	0.006564	0.050017	0.943419	0.12249	0.000852	0.002904	0.102240
70	2.7737	0.60716	555.713	527.79	2,250.78	9,267.90	39,516.36	19.88	19.00	915.25	557.29	53.95	53.301	53.261	0.9147	0.9141	0.005832	0.000586	0.01506	0.10246	1.92977	2.04729	0.007355	0.050049	0.942596	0.11857	0.000923	0.003143	0.117953
75	2.6795	0.58654	536.837	509.84	2,174.34	9,795.66	41,767.13	19.88	19.00	915.25	557.28	53.95	56.337	50.225	0.9668	0.8620	0.005942	0.000597	0.01585	0.09669	1.81806	1.93060	0.008209	0.050084	0.941708	0.11464	0.000994	0.003385	0.134878
80	2.5852	0.56590	517.949	491.89	2,097.85	10,305.48	43,941.46	19.88	19.00	915.26	557.27	53.95	59.270	47.292	1.0172	0.8116	0.006056	0.000609	0.01660	0.09111	1.71016	1.81787	0.009131	0.050121	0.940748	0.11071	0.001066	0.003631	0.153033
85	2.4909	0.54525	499.048	473.92	2,021.32	10,797.34	46,039.32	19.88	19.00	915.26	557.26	53.95	62.099	44.463	1.0657	0.7631	0.006173	0.000620	0.01731	0.08573	1.60607	1.70911	0.010128	0.050161	0.939710	0.10678	0.001139	0.003880	0.172434
90	2.3965	0.52458	480.134	455.94	1,944.73	11,271.23	48,060.63	19.88	19.00	915.26	557.25	53.95	64.825	41.737	1.1125	0.7163	0.006293	0.000633	0.01798	0.08055	1.50579	1.60432	0.011209	0.050205	0.938585	0.10284	0.001213	0.004132	0.193094
95	2.3020	0.50390	461.205	437.94	1,868.08	11,727.14	50,005.36	19.88	19.00	915.26	557.24	53.95	67.448	39.114	1.1575	0.6713	0.006415	0.000645	0.01862	0.07555	1.40932	1.50350	0.012383	0.050253	0.937364	0.09891	0.001288	0.004386	0.215026
100	2.2074	0.48319	442.259	419.93	1,791.36	12,165.05	51,873.43	19.88	19.00	915.26	557.22	53.95	69.968	36.594	1.2008	0.6280	0.006539	0.000657	0.01921	0.07076	1.31668	1.40665	0.013659	0.050305	0.936037	0.09497	0.001363	0.004643	0.238240
105	2.1127	0.46248	423.297	401.90	1,714.58	12,584.95	53,664.79	19.88	19.00	915.26	557.21	53.95	72.384	34.178	1.2422	0.5866	0.006665	0.000670	0.01977	0.06616	1.22785	1.31379	0.015048	0.050361	0.934591	0.09103	0.001439	0.004900	0.262741
110	2.0180	0.44173	404.315	383.85	1,637.72	12,986.82	55,379.37	19.88	19.00	915.26	557.20	53.95	74.696	31.866	1.2819	0.5469	0.006791	0.000683	0.02029	0.06176	1.14285	1.22490	0.016563	0.050422	0.933015	0.08708	0.001514	0.005158	0.288530
115	1.9231	0.42097	385.312	365.78	1,560.78	13,370.64	57,017.09	19.88	19.00	915.26	557.18	53.95	76.904	29.657	1.3198	0.5090	0.006918	0.000695	0.02077	0.05756	1.06168	1.14001	0.018217	0.050489	0.931293	0.08313	0.001590	0.005414	0.315601
120	1.8282	0.40018	366.287	347.69	1,483.74	13,736.39	58,577.86	19.88	19.00	915.26	557.17	53.95	79.009	27.553	1.3559	0.4729	0.007043	0.000708	0.02121	0.05355	0.98434	1.05910	0.020026	0.050563	0.929412	0.07918	0.001664	0.005667	0.343937
125	1.7331	0.37936	347.235	329.57	1,406.61	14,084.04	60,061.60	19.88	19.00	915.26	557.15	53.95	81.010	25.552	1.3903	0.4385	0.007164	0.000720	0.02161	0.04974	0.91083	0.98219	0.022005	0.050643	0.927352	0.07521	0.001737	0.005915	0.373511
130	1.6378	0.35851	328.155	311.42	1,329.36	14,413.58	61,468.20	19.88	18.99	915.26	557.14	53.95	82.907	23.655	1.4228	0.4060	0.007280	0.000732	0.02198	0.04613	0.84117	0.90928	0.024173	0.050731	0.925096	0.07124	0.001807	0.006154	0.404280
135	1.5424	0.33763	309.043	58.65	250.40	14,724.96	62,797.56	19.88	18.99	915.27	557.12	53.95	84.699	21.863	1.4536	0.3752	0.007387	0.000743	0.02231	0.04271	0.77535	0.84038	0.026548	0.050827	0.922624	0.01345	0.000361	0.006140	0.410421
136	1.5238	0.33355	305.309	57.93	247.37	14,783.59	63,047.96	19.88	18.99	915.27	557.11	53.95	85.037	21.525	1.4594	0.3694	0.007407	0.000745	0.02238	0.04207	0.76294	0.82740	0.027053	0.050848	0.922099	0.01330	0.000363	0.006184	0.416605
137	1.5051	0.32947	301.575	57.22	244.35	14,841.52	63,295.33	19.88	18.99	915.27	557.11	53.95	85.371	21.191	1.4651	0.3637	0.007426	0.000747	0.02246	0.04144	0.75069	0.81458	0.027567	0.050869	0.921564	0.01314	0.000366	0.006228	0.422833
138	1.4865	0.32539	297.841	56.51	241.33	14,898.74	63,539.68	19.88	18.99	915.27	557.10	53.95	85.700	20.862	1.4708	0.3580	0.007445	0.000749	0.02253	0.04081	0.73858	0.80191	0.028090	0.050890	0.921020	0.01299	0.000368	0.006271	0.429104
139	1.4678	0.32131	294.106	55.80	238.30	14,955.24	63,781.01	19.88	18.99	915.27	557.10	53.95	86.025	20.537	1.4764	0.3524	0.007463	0.000750	0.02259	0.04019	0.72662	0.78941	0.028623	0.050911	0.920466	0.01283	0.000371	0.006313	0.435417
140	1.4492	0.31723	290.371	55.09	235.28	15,011.04	64,019.31	19.88	18.99	915.27	557.10	53.96	86.347	20.215	1.4819	0.3469	0.007480	0.000752	0.02266	0.03958	0.71482	0.77706	0.029164	0.050933	0.919902	0.01267	0.000373	0.006354	0.441772
141	1.4304	0.31311	286.610	54.37	232.24	15,066.12	64,254.59	19.88	18.99	915.27	557.09	53.96	86.664	19.898	1.4873	0.3415	0.007496	0.000754	0.02273	0.03897	0.70316	0.76486	0.029716	0.050956	0.919329	0.01252	0.000375	0.006394	0.448166
142	1.4108	0.30881	282.675	53.62	229.05	15,120.49	64,486.83	19.87	18.99	915.27	557.09	53.96	86.977	19.585	1.4927	0.3361	0.007508	0.000755	0.02279	0.03838	0.69166	0.75283	0.030277	0.050979	0.918745	0.01235	0.000378	0.006429	0.454595
143	1.3900	0.30427	278.520	52.83	225.69	15,174.10	64,715.88	19.87	18.99	915.27	557.08	53.96	87.286	19.276	1.4980	0.3308	0.007514	0.000756	0.02286	0.03779	0.68031	0.74096	0.030847	0.051002	0.918151	0.01218	0.000379	0.006458	0.461053
144	1.3681	0.29946	274.118	51.99	222.12	15,226.93	64,941.56	19.87	18.99	915.27	557.08	53.96	87.590	18.972	1.5032	0.3256	0.007514	0.000756	0.02292	0.03721	0.66913	0.72926	0.031427	0.051025	0.917548	0.01199	0.000380	0.006479	0.467532
145	1.3447	0.29434	269.432	51.10	218.33	15,278.91	65,163.69	19.87	18.99	915.27	557.07	53.96	87.890	18.672	1.5083	0.3205	0.007506	0.000755	0.02298	0.03664	0.65813	0.71775	0.032016	0.051049	0.916935	0.01180	0.000381	0.006492	0.474024
146	1.3196	0.28886	264.417	50.15	214.27	15,330.01	65,382.01	19.87	18.99	915.27	557.07	53.96	88.184	18.378	1.5134	0.3154	0.007489	0.000753	0.02304	0.03608	0.64732	0.70644	0.032613	0.051073	0.916314	0.01158	0.000381	0.006494	0.480518
147	1.2927	0.28296	259.018	49.12	209.90	15,380.15	65,596.28	19.87	18.99	915.27	557.06	53.96	88.473	18.089	1.5184	0.3104	0.007461	0.000750	0.02310	0.03553	0.63671	0.69533	0.033217	0.051098	0.915685	0.01136	0.000381	0.006483	0.487001
148	1.2634	0.27656	253.161	48.01	205.15	15,429.26	65,806.18	19.87	18.99	915.27	557.06	53.96	88.756	17.806	1.5232	0.3056	0.007420	0.000746	0.02315	0.03499	0.62631	0.68446	0.033829	0.051123	0.915048	0.01111	0.000379	0.006458	0.493459
149	1.2314	0.26956	246.749	46.79	199.96	15,477.26	66,011.33	19.87	18.99	915.27	557.05	53.96	89.032	17.530	1.5280	0.3008	0.007362	0.000740	0.02321	0.03446	0.61615	0.67383	0.034447	0.051148	0.914406	0.01083	0.000377	0.006413	0.499872
150	1.1960	0.26180	239.647	45.44	194.21	15,524.04	66,211.29	19.87	18.99	915.27	557.05	53.96	89.302	17.260	1.5326	0.2962	0.007283	0.000732	0.02327	0.03395	0.60625	0.66347	0.035069	0.051173	0.913758	0.01053	0.000373	0.006345	0.506217
151	1.1561	0.25307	231.663	43.92	187.74	15,569.47	66,405.50	19.87	18.99	915.27	557.04	53.96	89.564	16.998	1.5371	0.2917	0.007178	0.000722	0.02332	0.03345	0.59663	0.65340	0.035693	0.051198	0.913109	0.01019	0.000367	0.006248	0.512465
152	1.1104	0.24307	222.507	42.18	180.33	15,613.39	66,593.24	19.87	18.99	915.27	557.03	53.96	89.817	16.745	1.5414	0.2874	0.007038	0.000708	0.02338	0.03297	0.58733	0.64368	0.036317	0.051224	0.912459	0.00980	0.000359	0.006110	0.518575
153	1.0565	0.23127	211.704	40.13	171.58	15,655.56	66,773.57	19.87	18.99	915.27	557.03	53.96	90.060	16.502	1.5456	0.2832	0.006847	0.000689	0.02343	0.03251	0.57839	0.63433	0.036938	0.051249	0.911813	0.00933	0.000347	0.005917	0.524492
154	0.9901	0.21672	198.393	37.60	160.79	15,695.68	66,945.15	19.87	18.99	915.27	557.02	53.96	90.291	16.271	1.5496	0.2792	0.006581	0.000662	0.02349	0.03207	0.56989	0.62544	0.037550	0.051274	0.911176	0.00875	0.000331	0.005642	0.530134
155	0.9018	0.19741	180.715	3.42	14.65	15,733.27	67,105.94	19.87	18.99	915.27	557.02	53.96	90.508	16.054	1.5533	0.2755	0.006183	0.000622	0.02354	0.03166	0.56192	0.61711	0.038147	0.051298	0.910555	0.00080	0.000030	0.005191	0.530654
155	0.8916	0.19517	178.667	3.39	14.48	15,736.70	67,120.59	19.87	18.99	915.27	557.02	53.96	90.527	16.035	1.5536	0.2752	0.006134	0.000617	0.02355	0.03162	0.56119	0.61636	0.038203	0.051300	0.910497	0.00079	0.000030	0.005141	0.531168
155	0.8810	0.19284	176.537	3.35	14.31	15,740.08	67,135.07	19.87	18.99	915.27	557.02	53.96	90.547	16.015	1.5540	0.2748	0.006083	0.000612	0.02355	0.03158	0.56047	0.61560	0.038259	0.051302	0.910438	0.00078	0.000030	0.005088	0.531677
155	0.8699	0.19042	174.316	3.30	14.13	15,743.43	67,149.38	19.87	18.99	915.27	557.02	53.96	90.566	15.996	1.5543	0.2745	0.006029	0.000606	0.02356	0.03155	0.55976	0.61486	0.038315	0.051305	0.910381	0.00077	0.000030	0.005032	0.532180
155	0.8583	0.18789	171.998	3.26	13.94	15,746.73	67,163.50	19.87	18.99	915.27	557.02	53.96	90.585	15.977	1.5546	0.2742	0.005972	0.000601	0.02356	0.03151	0.55906	0.61413	0.038370	0.051307	0.910323	0.00076	0.000029	0.004973	0.532677
156	0.8462	0.18524	169.572	3.21	13.74	15,749.99	67,177.44	19.87	18.99	915.27	557.02	53.96	90.604	15.958	1.5549	0.2739	0.005911	0.000595	0.02357	0.03147	0.55837	0.61341	0.038425	0.051309	0.910266	0.00075	0.000029	0.004911	0.533168
156	0.8335	0.18245	167.026	3.16	13.54	15,753.20	67,191.19	19.87	18.99	915.27	557.02	53.96	90.623	15.939	1.5552	0.2736	0.005847	0.000588	0.02358	0.03144	0.55768	0.61270	0.038479	0.051311	0.910210	0.00074	0.000028	0.004845	0.533653
156	0.8202	0.17953	164.349	3.11	13.32	15,756.37	67,204.73	19.87	18.99	915.27	557.01	53.96	90.641	15.921	1.5556	0.2732	0.005779	0.000581	0.02358	0.03140	0.55701	0.61200	0.038533	0.051314	0.910154	0.00073	0.000028	0.004775	0.534130
156	0.8061	0.17644	161.524	3.06	13.09	15,759.48	67,218.05	19.87	18.99	915.27	557.01	53.96	90.659	15.903	1.5559	0.2729	0.005707	0.000574	0.02359	0.03137	0.55635	0.61131	0.038586	0.051316	0.910099	0.00071	0.000028	0.004701	0.534600
156	0.7911	0.17318	158.535	3.00	12.85	15,762.54	67,231.14	19.87	18.99	915.27	557.01	53.96	90.676	15.886	1.5562	0.2726	0.005629	0.000566	0.02359	0.03134	0.55570	0.61063	0.038638	0.051318	0.910044	0.00070	0.000027	0.004621	0.535063
156.0	0.7753	0.16971	155.362	2.94	12.59	15,765.54	67,243.99	19.87	18.99	915.27	557.01	53.96	90.694	15.868	1.5565	0.2723	0.005546	0.000558	0.02360	0.03130	0.55506	0.60996	0.038690	0.051320	0.909990	0.00069	0.000027	0.004536	0.535516
156	0.7584	0.16602	151.984	2.88	12.32	15,768.48	67,256.58	19.87	18.99	915.27	557.01	53.96	90.711	15.851	1.5568	0.2720	0.005456	0.000549	0.02361	0.03127	0.55443	0.60931	0.038741	0.051322	0.909937	0.00067	0.000026	0.004445	0.535961
156	0.7404	0.16208	148.377	2.81	12.03	15,771.36	67,268.90	19.87	18.99	915.27	557.01	53.96	90.727	15.835	1.5570	0.2718	0.005359	0.000539	0.02361	0.03124	0.55382	0.60867	0.038792	0.051324	0.909884	0.00066	0.000026	0.004346	0.536395
156	0.7212	0.15787	144.523	2.74	11.71	15,774.17	67,280.93	19.87	18.99	915.27	557.01	53.96	90.743	15.818	1.5573	0.2715	0.005254	0.000528	0.02362	0.03121	0.55322	0.60805	0.038841	0.051326	0.909833	0.00064	0.000025	0.004240	0.536819
156	0.7007	0.15339	140.420	2.66	11.38	15,776.91	67,292.64	19.87	18.99	915.27	557.01	53.96	90.759	15.803	1.5576	0.2712	0.005142	0.000517	0.02362	0.03118	0.55264	0.60744	0.038890	0.051328	0.909782	0.00062	0.000024	0.004126	0.537232
157	0.6793	0.14870	136.130	5.16	22.07	15,779.57	67,304.02	19.87	18.99	915.27	557.01	53.96	90.775	15.787	1.5579	0.2709	0.005022	0.000505	0.02363	0.03115	0.55207	0.60685	0.038937	0.051330	0.909733	0.00121	0.000047	0.004009	0.538034
157	0.6454	0.14127	129.326	2.45	10.48	15,784.73	67,326.09	19.87	18.99	915.27	557.01	53.96	90.804	15.758	1.5584	0.2704	0.004833	0.000486	0.02364	0.03109	0.55097	0.60571	0.039030	0.051334	0.909636	0.00057	0.000022	0.003818	0.538415
157	0.7117	0.15580	142.627	2.70	11.56	15,787.18	67,336.57	19.87	18.99	915.27	557.01	53.96	90.818	15.744	1.5586	0.2702	0.005220	0.000525	0.02365	0.03107	0.55045	0.60517	0.039075	0.051336	0.909589	0.00063	0.000025	0.004211	0.538837
157	#NUM!	#NUM!	#NUM!	#NUM!	#NUM!	15,789.88	67,348.13	19.87	18.99	915.27	557.01	53.96	90.834	15.728	1.5589	0.2699	#NUM!	#NUM!	0.02365	0.03104	0.54988	0.60457	0.039124	0.051338	0.909539	#NUM!	#NUM!	#NUM!	#NUM!

Table B-1:

Leak Rate of Aqueous Ammonia from 8,000-Gallon Tank Truck through 3-inch Hole, 64°F

Tank Dimensions:			
Cylindrical Length	42.00 ft	Acceleration of Gravity	9.80665 m/s^2
	12.80 m	Initial Concentration	29.4 wt %
Diameter	6.00 ft	Solution Density	895.35 kg/m^3
	1.83 m	Initial Solution Mass	27,114 kg
Initial Solution Volume:	8,000 gal	Hole Diameter:	3.068 inches
	1,069.4 ft^3		0.0779272 m
	30.283 m^3	Hole Area	0.004769 m^2

Elapsed Time, sec	Mass, kg	Volume, m^3	Liquid Height, m	Angle, Radians	Liquid Volume, m^3 Cylinder	Liquid Volume, m^3 Heads	Volume Error	Outlet Leak Rate Velocity, m/s	Outlet Leak Rate m^3/s	Outlet Leak Rate kg/s	Cumul. Leak, kg
0	27,114	30.2833	1.5438	2.3299	30.2833	0.0000	0.0000	5.503	0.0262	23.50	0
10	26,879	30.0209	1.5285	2.3071	30.0209	0.0000	0.0000	5.475	0.0261	23.38	235
20	26,645	29.7597	1.5136	2.2853	29.7597	0.0000	0.0000	5.448	0.0260	23.27	469
30	26,413	29.4998	1.4990	2.2644	29.4999	0.0000	0.0000	5.422	0.0259	23.15	701
40	26,181	29.2412	1.4848	2.2443	29.2412	0.0000	0.0000	5.396	0.0257	23.04	933
50	25,951	28.9839	1.4708	2.2249	28.9839	0.0000	0.0000	5.371	0.0256	22.94	1,163
60	25,721	28.7277	1.4571	2.2062	28.7277	0.0000	0.0000	5.346	0.0255	22.83	1,393
70	25,493	28.4727	1.4437	2.1881	28.4727	0.0000	0.0000	5.321	0.0254	22.72	1,621
80	25,266	28.2189	1.4305	2.1705	28.2189	0.0000	0.0000	5.297	0.0253	22.62	1,848
90	25,040	27.9663	1.4175	2.1533	27.9663	0.0000	0.0000	5.273	0.0251	22.52	2,075
100	24,814	27.7148	1.4047	2.1367	27.7148	0.0000	0.0000	5.249	0.0250	22.41	2,300
110	24,590	27.4645	1.3921	2.1204	27.4645	0.0000	0.0000	5.225	0.0249	22.31	2,524
120	24,367	27.2153	1.3796	2.1046	27.2153	0.0000	0.0000	5.202	0.0248	22.21	2,747
130	24,145	26.9672	1.3674	2.0891	26.9672	0.0000	0.0000	5.179	0.0247	22.11	2,969
140	23,924	26.7202	1.3553	2.0739	26.7202	0.0000	0.0000	5.156	0.0246	22.02	3,190
150	23,704	26.4743	1.3434	2.0591	26.4743	0.0000	0.0000	5.133	0.0245	21.92	3,410
160	23,484	26.2295	1.3316	2.0445	26.2295	0.0000	0.0000	5.110	0.0244	21.82	3,630
170	23,266	25.9857	1.3199	2.0302	25.9857	0.0000	0.0000	5.088	0.0243	21.73	3,848
180	23,049	25.7431	1.3084	2.0162	25.7431	0.0000	0.0000	5.066	0.0242	21.63	4,065
190	22,833	25.5015	1.2970	2.0025	25.5015	0.0000	0.0000	5.044	0.0241	21.54	4,281
200	22,617	25.2609	1.2857	1.9889	25.2609	0.0000	0.0000	5.022	0.0240	21.44	4,497
210	22,403	25.0214	1.2745	1.9756	25.0214	0.0000	0.0000	5.000	0.0238	21.35	4,711
220	22,189	24.7829	1.2635	1.9625	24.7829	0.0000	0.0000	4.978	0.0237	21.26	4,925
230	21,977	24.5455	1.2525	1.9496	24.5455	0.0000	0.0000	4.956	0.0236	21.17	5,137
240	21,765	24.3091	1.2417	1.9369	24.3091	0.0000	0.0000	4.935	0.0235	21.07	5,349
250	21,554	24.0737	1.2310	1.9243	24.0737	0.0000	0.0000	4.914	0.0234	20.98	5,560
260	21,345	23.8394	1.2203	1.9119	23.8394	0.0000	0.0000	4.892	0.0233	20.89	5,770
270	21,136	23.6061	1.2098	1.8997	23.6061	0.0000	0.0000	4.871	0.0232	20.80	5,978
280	20,928	23.3737	1.1993	1.8876	23.3737	0.0000	0.0000	4.850	0.0231	20.71	6,186
290	20,720	23.1424	1.1889	1.8757	23.1424	0.0000	0.0000	4.829	0.0230	20.62	6,394
300	20,514	22.9121	1.1786	1.8639	22.9121	0.0000	0.0000	4.808	0.0229	20.53	6,600

Table B-1:

Leak Rate of Aqueous Ammonia from 8,000-Gallon Tank Truck through 3-inch Hole, 64°F

Tank Dimensions:			
Cylindrical Length	42.00 ft	Acceleration of Gravity	9.80665 m/s^2
	12.80 m	Initial Concentration	29.4 wt %
Diameter	6.00 ft	Solution Density	895.35 kg/m^3
	1.83 m	Initial Solution Mass	27,114 kg
Initial Solution Volume:	8,000 gal	Hole Diameter:	3.068 inches
	1,069.4 ft^3		0.0779272 m
	30.283 m^3	Hole Area	0.004769 m^2

Elapsed Time, sec	Mass, kg	Volume, m^3	Liquid Height, m	Angle, Radians	Liquid Volume, m^3 Cylinder	Liquid Volume, m^3 Heads	Volume Error	Outlet Leak Rate Velocity, m/s	Outlet Leak Rate m^3/s	Outlet Leak Rate kg/s	Cumul. Leak, kg
310	20,309	22.6828	1.1684	1.8523	22.6828	0.0000	0.0000	4.787	0.0228	20.44	6,805
320	20,105	22.4545	1.1583	1.8408	22.4545	0.0000	0.0000	4.766	0.0227	20.35	7,010
330	19,901	22.2271	1.1482	1.8294	22.2271	0.0000	0.0000	4.746	0.0226	20.26	7,213
340	19,698	22.0008	1.1382	1.8181	22.0008	0.0000	0.0000	4.725	0.0225	20.18	7,416
350	19,497	21.7755	1.1283	1.8069	21.7755	0.0000	0.0000	4.704	0.0224	20.09	7,617
360	19,296	21.5511	1.1185	1.7959	21.5511	0.0000	0.0000	4.684	0.0223	20.00	7,818
370	19,096	21.3277	1.1087	1.7849	21.3277	0.0000	0.0000	4.663	0.0222	19.91	8,018
380	18,897	21.1053	1.0990	1.7741	21.1053	0.0000	0.0000	4.643	0.0221	19.83	8,217
390	18,698	20.8839	1.0893	1.7633	20.8839	0.0000	0.0000	4.622	0.0220	19.74	8,416
400	18,501	20.6634	1.0798	1.7526	20.6634	0.0000	0.0000	4.602	0.0219	19.65	8,613
410	18,304	20.4439	1.0702	1.7420	20.4439	0.0000	0.0000	4.582	0.0219	19.56	8,810
420	18,109	20.2254	1.0608	1.7316	20.2254	0.0000	0.0000	4.561	0.0218	19.48	9,005
430	17,914	20.0079	1.0514	1.7211	20.0079	0.0000	0.0000	4.541	0.0217	19.39	9,200
440	17,720	19.7913	1.0420	1.7108	19.7913	0.0000	0.0000	4.521	0.0216	19.31	9,394
450	17,527	19.5757	1.0327	1.7006	19.5757	0.0000	0.0000	4.501	0.0215	19.22	9,587
460	17,335	19.3610	1.0235	1.6904	19.3610	0.0000	0.0000	4.480	0.0214	19.13	9,779
470	17,143	19.1473	1.0143	1.6803	19.1473	0.0000	0.0000	4.460	0.0213	19.05	9,971
480	16,953	18.9346	1.0052	1.6702	18.9346	0.0000	0.0000	4.440	0.0212	18.96	10,161
490	16,763	18.7228	0.9961	1.6602	18.7228	0.0000	0.0000	4.420	0.0211	18.87	10,351
500	16,575	18.5120	0.9870	1.6503	18.5120	0.0000	0.0000	4.400	0.0210	18.79	10,539
510	16,387	18.3022	0.9780	1.6405	18.3022	0.0000	0.0000	4.380	0.0209	18.70	10,727
520	16,200	18.0933	0.9691	1.6307	18.0933	0.0000	0.0000	4.360	0.0208	18.62	10,914
530	16,014	17.8853	0.9602	1.6209	17.8853	0.0000	0.0000	4.340	0.0207	18.53	11,100
540	15,828	17.6784	0.9514	1.6112	17.6784	0.0000	0.0000	4.320	0.0206	18.45	11,286
550	15,644	17.4723	0.9425	1.6016	17.4723	0.0000	0.0000	4.300	0.0205	18.36	11,470
560	15,460	17.2673	0.9338	1.5920	17.2673	0.0000	0.0000	4.280	0.0204	18.28	11,654
570	15,277	17.0632	0.9251	1.5825	17.0632	0.0000	0.0000	4.260	0.0203	18.19	11,837
580	15,096	16.8600	0.9164	1.5730	16.8600	0.0000	0.0000	4.240	0.0202	18.10	12,018
590	14,915	16.6578	0.9078	1.5635	16.6578	0.0000	0.0000	4.219	0.0201	18.02	12,200
600	14,734	16.4566	0.8992	1.5541	16.4566	0.0000	0.0000	4.199	0.0200	17.93	12,380

Table B-1:

Leak Rate of Aqueous Ammonia from 8,000-Gallon Tank Truck through 3-inch Hole, 64°F

Tank Dimensions:			
Cylindrical Length	42.00 ft	Acceleration of Gravity	9.80665 m/s²
	12.80 m	Initial Concentration	29.4 wt %
Diameter	6.00 ft	Solution Density	895.35 kg/m³
	1.83 m	Initial Solution Mass	27,114 kg
Initial Solution Volume:	8,000 gal	Hole Diameter:	3.068 inches
	1,069.4 ft³		0.0779272 m
	30.283 m³	Hole Area	0.004769 m²

Elapsed Time, sec	Mass, kg	Volume, m³	Liquid Height, m	Angle, Radians	Liquid Volume, m³ Cylinder	Liquid Volume, m³ Heads	Volume Error	Outlet Leak Rate Velocity, m/s	Outlet Leak Rate m³/s	Outlet Leak Rate kg/s	Cumul. Leak, kg
610	14,555	16.2563	0.8906	1.5448	16.2563	0.0000	0.0000	4.179	0.0199	17.85	12,559
620	14,377	16.0569	0.8821	1.5354	16.0569	0.0000	0.0000	4.159	0.0198	17.76	12,738
630	14,199	15.8586	0.8736	1.5262	15.8586	0.0000	0.0000	4.139	0.0197	17.68	12,915
640	14,022	15.6611	0.8652	1.5169	15.6611	0.0000	0.0000	4.119	0.0196	17.59	13,092
650	13,846	15.4647	0.8568	1.5077	15.4647	0.0000	0.0000	4.099	0.0196	17.50	13,268
660	13,671	15.2692	0.8484	1.4985	15.2692	0.0000	0.0000	4.079	0.0195	17.42	13,443
670	13,497	15.0746	0.8400	1.4894	15.0746	0.0000	0.0000	4.059	0.0194	17.33	13,617
680	13,324	14.8810	0.8317	1.4803	14.8810	0.0000	0.0000	4.039	0.0193	17.25	13,790
690	13,151	14.6884	0.8235	1.4712	14.6884	0.0000	0.0000	4.019	0.0192	17.16	13,963
700	12,980	14.4967	0.8152	1.4621	14.4967	0.0000	0.0000	3.999	0.0191	17.08	14,134
710	12,809	14.3060	0.8070	1.4531	14.3060	0.0000	0.0000	3.979	0.0190	16.99	14,305
720	12,639	14.1162	0.7989	1.4441	14.1162	0.0000	0.0000	3.958	0.0189	16.90	14,475
730	12,470	13.9274	0.7907	1.4352	13.9274	0.0000	0.0000	3.938	0.0188	16.82	14,644
740	12,302	13.7396	0.7826	1.4262	13.7396	0.0000	0.0000	3.918	0.0187	16.73	14,812
750	12,134	13.5527	0.7746	1.4173	13.5527	0.0000	0.0000	3.898	0.0186	16.64	14,980
760	11,968	13.3668	0.7665	1.4084	13.3668	0.0000	0.0000	3.877	0.0185	16.56	15,146
770	11,802	13.1819	0.7585	1.3995	13.1819	0.0000	0.0000	3.857	0.0184	16.47	15,312
780	11,638	12.9979	0.7505	1.3906	12.9979	0.0000	0.0000	3.837	0.0183	16.38	15,476
790	11,474	12.8150	0.7426	1.3818	12.8150	0.0000	0.0000	3.816	0.0182	16.30	15,640
800	11,311	12.6329	0.7347	1.3730	12.6329	0.0000	0.0000	3.796	0.0181	16.21	15,803
810	11,149	12.4519	0.7268	1.3641	12.4519	0.0000	0.0000	3.776	0.0180	16.12	15,965
820	10,988	12.2718	0.7189	1.3553	12.2718	0.0000	0.0000	3.755	0.0179	16.04	16,127
830	10,827	12.0927	0.7111	1.3466	12.0927	0.0000	0.0000	3.734	0.0178	15.95	16,287
840	10,668	11.9146	0.7033	1.3378	11.9146	0.0000	0.0000	3.714	0.0177	15.86	16,446
850	10,509	11.7375	0.6955	1.3290	11.7375	0.0000	0.0000	3.693	0.0176	15.77	16,605
860	10,351	11.5613	0.6877	1.3203	11.5613	0.0000	0.0000	3.673	0.0175	15.68	16,763
870	10,195	11.3862	0.6800	1.3115	11.3862	0.0000	0.0000	3.652	0.0174	15.59	16,919
880	10,039	11.2120	0.6723	1.3028	11.2120	0.0000	0.0000	3.631	0.0173	15.51	17,075
890	9,884	11.0388	0.6646	1.2941	11.0388	0.0000	0.0000	3.610	0.0172	15.42	17,230
900	9,729	10.8666	0.6569	1.2854	10.8666	0.0000	0.0000	3.590	0.0171	15.33	17,385

Table B-1:

Leak Rate of Aqueous Ammonia from 8,000-Gallon Tank Truck through 3-inch Hole, 64°F

Tank Dimensions:			
Cylindrical Length	42.00 ft	Acceleration of Gravity	9.80665 m/s^2
	12.80 m	Initial Concentration	29.4 wt %
Diameter	6.00 ft	Solution Density	895.35 kg/m^3
	1.83 m	Initial Solution Mass	27,114 kg
Initial Solution Volume:	8,000 gal	Hole Diameter:	3.068 inches
	1,069.4 ft^3		0.0779272 m
	30.283 m^3	Hole Area	0.004769 m^2

Elapsed Time, sec	Mass, kg	Volume, m^3	Liquid Height, m	Angle, Radians	Liquid Volume, m^3 Cylinder	Liquid Volume, m^3 Heads	Volume Error	Outlet Leak Rate Velocity, m/s	Outlet Leak Rate m^3/s	Outlet Leak Rate kg/s	Cumul. Leak, kg
910	9,576	10.6954	0.6493	1.2767	10.6954	0.0000	0.0000	3.569	0.0170	15.24	17,538
920	9,424	10.5252	0.6417	1.2680	10.5252	0.0000	0.0000	3.548	0.0169	15.15	17,690
930	9,272	10.3560	0.6341	1.2593	10.3560	0.0000	0.0000	3.527	0.0168	15.06	17,842
940	9,122	10.1878	0.6266	1.2506	10.1878	0.0000	0.0000	3.506	0.0167	14.97	17,992
950	8,972	10.0206	0.6190	1.2419	10.0206	0.0000	0.0000	3.484	0.0166	14.88	18,142
960	8,823	9.8544	0.6115	1.2332	9.8544	0.0000	0.0000	3.463	0.0165	14.79	18,291
970	8,675	9.6892	0.6040	1.2245	9.6892	0.0000	0.0000	3.442	0.0164	14.70	18,439
980	8,528	9.5251	0.5966	1.2158	9.5251	0.0000	0.0000	3.421	0.0163	14.61	18,586
990	8,382	9.3619	0.5891	1.2071	9.3619	0.0000	0.0000	3.399	0.0162	14.52	18,732
1000	8,237	9.1998	0.5817	1.1984	9.1998	0.0000	0.0000	3.378	0.0161	14.42	18,877
1010	8,093	9.0387	0.5743	1.1897	9.0387	0.0000	0.0000	3.356	0.0160	14.33	19,021
1020	7,949	8.8786	0.5669	1.1810	8.8786	0.0000	0.0000	3.335	0.0159	14.24	19,165
1030	7,807	8.7196	0.5596	1.1723	8.7196	0.0000	0.0000	3.313	0.0158	14.15	19,307
1040	7,666	8.5616	0.5522	1.1636	8.5616	0.0000	0.0000	3.291	0.0157	14.05	19,448
1050	7,525	8.4046	0.5449	1.1548	8.4046	0.0000	0.0000	3.269	0.0156	13.96	19,589
1060	7,385	8.2487	0.5376	1.1461	8.2487	0.0000	0.0000	3.247	0.0155	13.87	19,729
1070	7,247	8.0938	0.5303	1.1373	8.0938	0.0000	0.0000	3.225	0.0154	13.77	19,867
1080	7,109	7.9400	0.5231	1.1286	7.9400	0.0000	0.0000	3.203	0.0153	13.68	20,005
1090	6,972	7.7872	0.5158	1.1198	7.7872	0.0000	0.0000	3.181	0.0152	13.58	20,142
1100	6,836	7.6355	0.5086	1.1110	7.6355	0.0000	0.0000	3.158	0.0151	13.49	20,278
1110	6,702	7.4849	0.5014	1.1022	7.4849	0.0000	0.0000	3.136	0.0150	13.39	20,412
1120	6,568	7.3353	0.4943	1.0934	7.3353	0.0000	0.0000	3.114	0.0148	13.30	20,546
1130	6,435	7.1868	0.4871	1.0846	7.1868	0.0000	0.0000	3.091	0.0147	13.20	20,679
1140	6,303	7.0394	0.4800	1.0757	7.0394	0.0000	0.0000	3.068	0.0146	13.10	20,811
1150	6,172	6.8931	0.4728	1.0668	6.8931	0.0000	0.0000	3.045	0.0145	13.00	20,942
1160	6,042	6.7478	0.4657	1.0580	6.7478	0.0000	0.0000	3.022	0.0144	12.91	21,072
1170	5,913	6.6037	0.4587	1.0490	6.6037	0.0000	0.0000	2.999	0.0143	12.81	21,201
1180	5,784	6.4606	0.4516	1.0401	6.4606	0.0000	0.0000	2.976	0.0142	12.71	21,330
1190	5,657	6.3187	0.4445	1.0311	6.3187	0.0000	0.0000	2.953	0.0141	12.61	21,457
1200	5,531	6.1778	0.4375	1.0222	6.1778	0.0000	0.0000	2.929	0.0140	12.51	21,583

Table B-1:

Leak Rate of Aqueous Ammonia from 8,000-Gallon Tank Truck through 3-inch Hole, 64°F

Tank Dimensions:			
Cylindrical Length	42.00 ft	Acceleration of Gravity	9.80665 m/s²
	12.80 m	Initial Concentration	29.4 wt %
Diameter	6.00 ft	Solution Density	895.35 kg/m³
	1.83 m	Initial Solution Mass	27,114 kg
Initial Solution Volume:	8,000 gal	Hole Diameter:	3.068 inches
	1,069.4 ft³		0.0779272 m
	30.283 m³	Hole Area	0.004769 m²

Elapsed Time, sec	Mass, kg	Volume, m³	Liquid Height, m	Angle, Radians	Liquid Volume, m³ Cylinder	Liquid Volume, m³ Heads	Volume Error	Outlet Leak Rate Velocity, m/s	Outlet Leak Rate m³/s	Outlet Leak Rate kg/s	Cumul. Leak, kg
1210	5,406	6.0381	0.4305	1.0131	6.0381	0.0000	0.0000	2.906	0.0139	12.41	21,708
1220	5,282	5.8995	0.4235	1.0041	5.8995	0.0000	0.0000	2.882	0.0137	12.31	21,832
1230	5,159	5.7621	0.4165	0.9950	5.7621	0.0000	0.0000	2.858	0.0136	12.21	21,955
1240	5,037	5.6258	0.4096	0.9859	5.6258	0.0000	0.0000	2.834	0.0135	12.10	22,077
1250	4,916	5.4906	0.4026	0.9768	5.4906	0.0000	0.0000	2.810	0.0134	12.00	22,198
1260	4,796	5.3566	0.3957	0.9676	5.3566	0.0000	0.0000	2.786	0.0133	11.90	22,318
1270	4,677	5.2237	0.3888	0.9584	5.2237	0.0000	0.0000	2.761	0.0132	11.79	22,437
1280	4,559	5.0920	0.3819	0.9491	5.0920	0.0000	0.0000	2.737	0.0131	11.69	22,555
1290	4,442	4.9615	0.3750	0.9399	4.9615	0.0000	0.0000	2.712	0.0129	11.58	22,672
1300	4,326	4.8321	0.3681	0.9305	4.8321	0.0000	0.0000	2.687	0.0128	11.47	22,788
1310	4,212	4.7040	0.3613	0.9212	4.7040	0.0000	0.0000	2.662	0.0127	11.37	22,902
1320	4,098	4.5770	0.3544	0.9117	4.5770	0.0000	0.0000	2.637	0.0126	11.26	23,016
1330	3,985	4.4512	0.3476	0.9023	4.4512	0.0000	0.0000	2.611	0.0125	11.15	23,129
1340	3,874	4.3267	0.3408	0.8927	4.3267	0.0000	0.0000	2.585	0.0123	11.04	23,240
1350	3,763	4.2034	0.3340	0.8832	4.2034	0.0000	0.0000	2.560	0.0122	10.93	23,351
1360	3,654	4.0813	0.3273	0.8735	4.0813	0.0000	0.0000	2.533	0.0121	10.82	23,460
1370	3,546	3.9605	0.3205	0.8639	3.9605	0.0000	0.0000	2.507	0.0120	10.71	23,568
1380	3,439	3.8409	0.3137	0.8541	3.8409	0.0000	0.0000	2.481	0.0118	10.59	23,675
1390	3,333	3.7226	0.3070	0.8443	3.7226	0.0000	0.0000	2.454	0.0117	10.48	23,781
1400	3,228	3.6056	0.3003	0.8344	3.6056	0.0000	0.0000	2.427	0.0116	10.36	23,886
1410	3,125	3.4898	0.2936	0.8245	3.4898	0.0000	0.0000	2.400	0.0114	10.25	23,989
1420	3,022	3.3754	0.2869	0.8145	3.3754	0.0000	0.0000	2.372	0.0113	10.13	24,092
1430	2,921	3.2622	0.2802	0.8044	3.2622	0.0000	0.0000	2.344	0.0112	10.01	24,193
1440	2,821	3.1504	0.2736	0.7942	3.1504	0.0000	0.0000	2.316	0.0110	9.89	24,293
1450	2,722	3.0399	0.2669	0.7840	3.0399	0.0000	0.0000	2.288	0.0109	9.77	24,392
1460	2,624	2.9308	0.2603	0.7737	2.9308	0.0000	0.0000	2.259	0.0108	9.65	24,490
1470	2,528	2.8230	0.2537	0.7633	2.8230	0.0000	0.0000	2.231	0.0106	9.52	24,586
1480	2,432	2.7167	0.2471	0.7527	2.7167	0.0000	0.0000	2.201	0.0105	9.40	24,682
1490	2,338	2.6117	0.2405	0.7421	2.6117	0.0000	0.0000	2.172	0.0104	9.27	24,776
1500	2,246	2.5081	0.2339	0.7314	2.5081	0.0000	0.0000	2.142	0.0102	9.15	24,868

Table B-1:

Leak Rate of Aqueous Ammonia from 8,000-Gallon Tank Truck through 3-inch Hole, 64°F

Tank Dimensions:			
Cylindrical Length	42.00 ft	Acceleration of Gravity	9.80665 m/s²
	12.80 m	Initial Concentration	29.4 wt %
Diameter	6.00 ft	Solution Density	895.35 kg/m³
	1.83 m	Initial Solution Mass	27,114 kg
Initial Solution Volume:	8,000 gal	Hole Diameter:	3.068 inches
	1,069.4 ft³		0.0779272 m
	30.283 m³	Hole Area	0.004769 m²

Elapsed Time, sec	Mass, kg	Volume, m³	Liquid Height, m	Angle, Radians	Liquid Volume, m³ Cylinder	Liquid Volume, m³ Heads	Volume Error	Outlet Leak Rate Velocity, m/s	Outlet Leak Rate m³/s	Outlet Leak Rate kg/s	Cumul. Leak, kg
1510	2,154	2.4059	0.2273	0.7206	2.4059	0.0000	0.0000	2.111	0.0101	9.02	24,960
1520	2,064	2.3052	0.2207	0.7096	2.3052	0.0000	0.0000	2.081	0.0099	8.89	25,050
1530	1,975	2.2060	0.2142	0.6986	2.2060	0.0000	0.0000	2.050	0.0098	8.75	25,139
1540	1,888	2.1082	0.2077	0.6874	2.1082	0.0000	0.0000	2.018	0.0096	8.62	25,226
1550	1,801	2.0120	0.2011	0.6761	2.0120	0.0000	0.0000	1.986	0.0095	8.48	25,313
1560	1,717	1.9173	0.1946	0.6646	1.9173	0.0000	0.0000	1.954	0.0093	8.34	25,397
1570	1,633	1.8241	0.1881	0.6530	1.8241	0.0000	0.0000	1.921	0.0092	8.20	25,481
1580	1,551	1.7325	0.1816	0.6412	1.7325	0.0000	0.0000	1.887	0.0090	8.06	25,563
1590	1,471	1.6424	0.1751	0.6293	1.6424	0.0000	0.0000	1.853	0.0088	7.91	25,643
1600	1,391	1.5540	0.1687	0.6171	1.5540	0.0000	0.0000	1.819	0.0087	7.77	25,723
1610	1,314	1.4673	0.1622	0.6048	1.4673	0.0000	0.0000	1.784	0.0085	7.62	25,800
1620	1,238	1.3822	0.1558	0.5923	1.3822	0.0000	0.0000	1.748	0.0083	7.46	25,876
1630	1,163	1.2989	0.1493	0.5796	1.2989	0.0000	0.0000	1.711	0.0082	7.31	25,951
1640	1,090	1.2172	0.1429	0.5666	1.2172	0.0000	0.0000	1.674	0.0080	7.15	26,024
1650	1,018	1.1374	0.1365	0.5534	1.1374	0.0000	0.0000	1.636	0.0078	6.99	26,096
1660	948	1.0594	0.1301	0.5399	1.0594	0.0000	0.0000	1.597	0.0076	6.82	26,166
1670	880	0.9832	0.1237	0.5261	0.9832	0.0000	0.0000	1.557	0.0074	6.65	26,234
1680	814	0.9089	0.1173	0.5120	0.9089	0.0000	0.0000	1.517	0.0072	6.48	26,300
1690	749	0.8366	0.1109	0.4976	0.8366	0.0000	0.0000	1.475	0.0070	6.30	26,365
1700	686	0.7662	0.1045	0.4828	0.7662	0.0000	0.0000	1.432	0.0068	6.11	26,428
1710	625	0.6980	0.0981	0.4675	0.6980	0.0000	0.0000	1.387	0.0066	5.92	26,489
1720	566	0.6318	0.0918	0.4518	0.6318	0.0000	0.0000	1.341	0.0064	5.73	26,548
1730	508	0.5678	0.0854	0.4356	0.5678	0.0000	0.0000	1.294	0.0062	5.53	26,606
1740	453	0.5061	0.0790	0.4188	0.5061	0.0000	0.0000	1.245	0.0059	5.32	26,661
1750	400	0.4467	0.0727	0.4014	0.4467	0.0000	0.0000	1.194	0.0057	5.10	26,714
1760	349	0.3898	0.0663	0.3832	0.3898	0.0000	0.0000	1.140	0.0054	4.87	26,765
1770	300	0.3354	0.0599	0.3641	0.3354	0.0000	0.0000	1.084	0.0052	4.63	26,814
1780	254	0.2837	0.0536	0.3440	0.2837	0.0000	0.0000	1.025	0.0049	4.38	26,860
1790	210	0.2348	0.0472	0.3227	0.2348	0.0000	0.0000	0.962	0.0046	4.11	26,904
1800	169	0.1889	0.0408	0.2998	0.1889	0.0000	0.0000	0.894	0.0043	3.82	26,945

Table B-1:

Leak Rate of Aqueous Ammonia from 8,000-Gallon Tank Truck through 3-inch Hole, 64°F

Tank Dimensions:			
Cylindrical Length	42.00 ft	Acceleration of Gravity	9.80665 m/s^2
	12.80 m	Initial Concentration	29.4 wt %
Diameter	6.00 ft	Solution Density	895.35 kg/m^3
	1.83 m	Initial Solution Mass	27,114 kg
Initial Solution Volume:	8,000 gal	Hole Diameter:	3.068 inches
	1,069.4 ft^3		0.0779272 m
	30.283 m^3	Hole Area	0.004769 m^2

Elapsed Time, sec	Mass, kg	Volume, m^3	Liquid Height, m	Angle, Radians	Liquid Volume, m^3 Cylinder	Liquid Volume, m^3 Heads	Volume Error	Outlet Leak Rate Velocity, m/s	Outlet Leak Rate m^3/s	Outlet Leak Rate kg/s	Cumul. Leak, kg
1805	150	0.1676	0.0376	0.2880	0.1676	0.0000	0.0000	0.859	0.0041	3.67	26,964
1810	132	0.1471	0.0345	0.2756	0.1471	0.0000	0.0000	0.823	0.0039	3.51	26,982
1815	114	0.1275	0.0313	0.2626	0.1275	0.0000	0.0000	0.784	0.0037	3.35	27,000
1820	97	0.1088	0.0282	0.2490	0.1088	0.0000	0.0000	0.744	0.0035	3.18	27,017
1825	81	0.0910	0.0250	0.2345	0.0910	0.0000	0.0000	0.701	0.0033	2.99	27,033
1830	67	0.0743	0.0219	0.2191	0.0743	0.0000	0.0000	0.655	0.0031	2.80	27,047
1835	52.6	0.0587	0.0187	0.2024	0.0587	0.0000	0.0000	0.605	0.0029	2.58	27,061
1840	39.6	0.0443	0.0155	0.1842	0.0443	0.0000	0.0000	0.551	0.0026	2.35	27,074
1845	27.9	0.0311	0.0122	0.1637	0.0311	0.0000	0.0000	0.490	0.0023	2.09	27,086
1850	17.4	0.0195	0.0089	0.1399	0.0195	0.0000	0.0000	0.419	0.0020	1.79	27,097
1851	15.6	0.0175	0.0083	0.1349	0.0175	0.0000	0.0000	0.404	0.0019	1.72	27,098
1852	13.9	0.0155	0.0077	0.1298	0.0155	0.0000	0.0000	0.388	0.0019	1.66	27,100
1853	12.3	0.0137	0.0071	0.1244	0.0137	0.0000	0.0000	0.372	0.0018	1.59	27,102
1854	10.7	0.0119	0.0064	0.1187	0.0119	0.0000	0.0000	0.355	0.0017	1.52	27,103
1855	9.1	0.0102	0.0058	0.1128	0.0102	0.0000	0.0000	0.338	0.0016	1.44	27,105
1856	7.7	0.0086	0.0052	0.1065	0.0086	0.0000	0.0000	0.319	0.0015	1.36	27,106
1857	6.3	0.0071	0.0046	0.0999	0.0071	0.0000	0.0000	0.299	0.0014	1.28	27,108
1858	5.1	0.0057	0.0039	0.0926	0.0057	0.0000	0.0000	0.277	0.0013	1.18	27,109
1859	3.9	0.0043	0.0033	0.0847	0.0043	0.0000	0.0000	0.254	0.0012	1.08	27,110
1860	2.8	0.0031	0.0026	0.0760	0.0031	0.0000	0.0000	0.227	0.0011	0.97	27,111
1861	1.8	0.0020	0.0020	0.0659	0.0020	0.0000	0.0000	0.197	0.0009	0.84	27,112
1862	1.0	0.0011	0.0013	0.0537	0.0011	0.0000	0.0000	0.161	0.0008	0.69	27,113
1863	0.3	0.0003	0.0006	0.0361	0.0003	0.0000	0.0000	0.108	0.0005	0.46	27,114
1863.6	0.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.000	0.0000	0.00	27,114

Table B-2:
Alternate-Case Aqueous Ammonia Release into Sump
Initial Evaporation Rate Calculation: 21'x16' Wetted Area

Sump Dimensions:		
Wetted Length	21.00	ft
	6.40	m
Sump Width	16	ft
	4.88	m
Equivalent Radius	3.152	m
Molecular Weight:		
NH_3	17.03	kg/kmol
H_2O	18.016	kg/kmol
Temperature	64	°F
	17.78	°C
	290.93	°K
Wind Speed	2.50	m/s
Solution Concentration	19	wt %
	19.88	mol %
Vapor Pressures:		
NH_3	157.818	mmHg
H_2O	11.941	mmHg
Evaporation Rates: (OCAG equation):		
NH_3	2.5399E-2	lb/min-ft^2
	2.0668E-3	kg/s-m^2
Wetted Area	6.4517E-2	kg/s
H_2O	1.9953E-3	lb/min-ft^2
	1.6236E-4	kg/s-m^2
Wetted Area	5.0682E-3	kg/s
Maximum Liquid Input to Sump:		
Total	23.498	kg/s
NH_3	4.465	kg/s
H_2O	19.033	kg/s
Evaporation Rate / Liquid Input:		
NH_3	1.4451E-2	
H_2O	2.6629E-4	
Final Solution Concentration	18.7811	wt%
Source Radius Calculation:		
Humid Air Density	1.22186	kg/m^3
Ammonia Source Radius	0.0820	m

Table C-1:
Avenal, CA: Two 24" Drains,
Endpoint Distance Interpolation for
24,000-Gallon Instantaneous Spill into 52x24 ft Sump, Plastic Balls:
1.5 m/s Wind, Rural Roughness

Total Ammonia Emission	7.795	kg
Maximum Emission Rate	0.05477	kg/s
Emission Duration	156.90	s
Average Emission Rate	0.04968	kg/s
Duration at Maximum Rate	142.31	s

Threshold Name	Threshold Conc, ppm	Averaging Time, Min	C^2t ppm^2-min	Equiv. Conc at Duration	Straddling Distances		Straddling Conc.		Endpoint Distance	
					X_1, m	X_2, m	C_1, m	C_2, m	Meters	Feet
Lethal	2000	30	1.200E+8	7,113	35.5	50.5	13,680	6,788	**49**	**162**
IDLH	300	30	2.700E+6	1,067	119	139	1,282	949.6	**131**	**429**
ERPG-2	200	60	2.400E+6	1,006	119	139	1,282	949.6	**135**	**443**
Short Term Public Emergency Limit	75	30	1.688E+5	266.7	259	279	287.4	249.2	**269**	**883**

Table C-2:
Avenal CA
Endpoint Distances for Alternative Release Scenario

Threshold	ERPG-2	STPEL
Limit, ppm	200	75
Straddling Distances, m		
Lower	225	385
Higher	245	405
Straddling Concentrations, ppm		
Higher	226.9	81.97
Lower	193.1	74.47
Interpolated Endpoint		
Meters	240.5	403.5
Feet	789	1,324

SHEET NO. 1 OF

PROJECT NO. 98-715

DATE

BY

CHK'D 11 Apr 99 by CJW

TRC

SUBJECT Falling-Film Flow in Sump

Figure 1. Sump Design (Top View)
Probable Flow Pattern

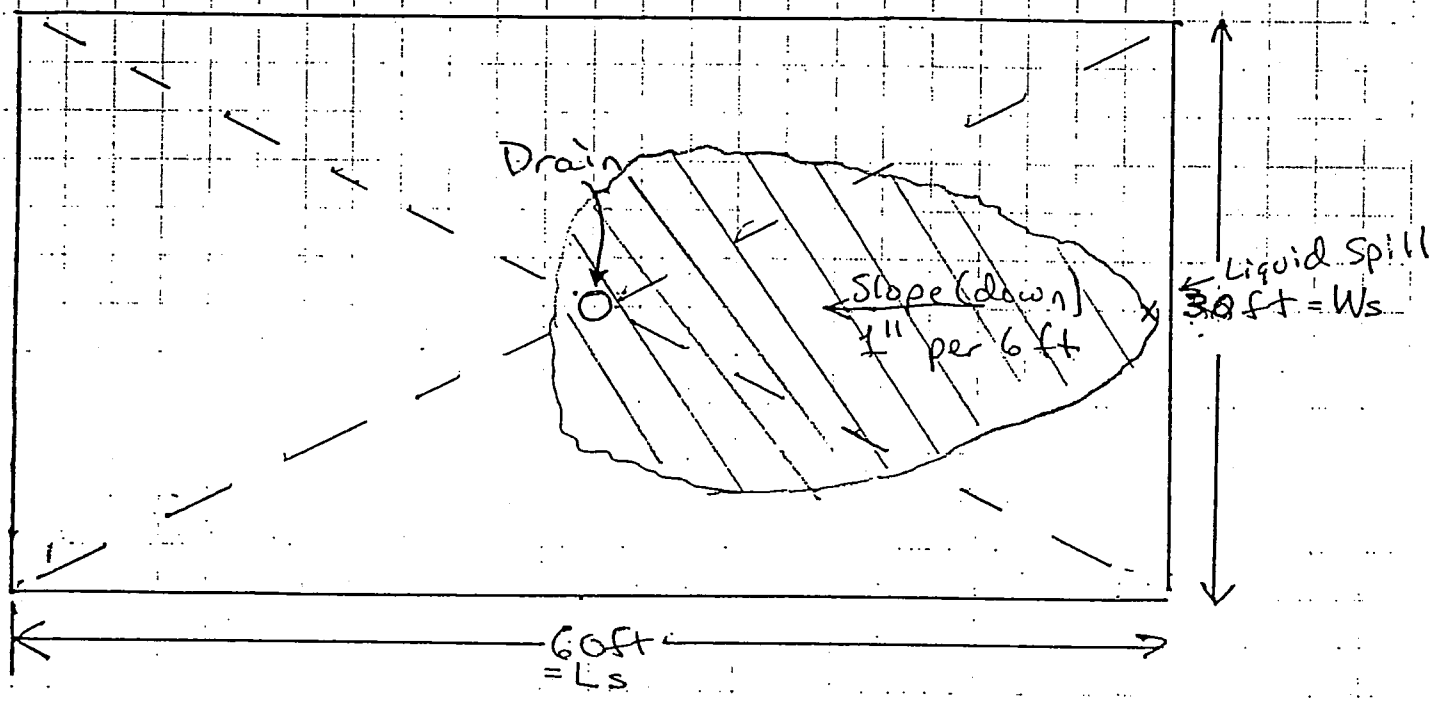

Figure 2. Falling Film Flow as Modeled

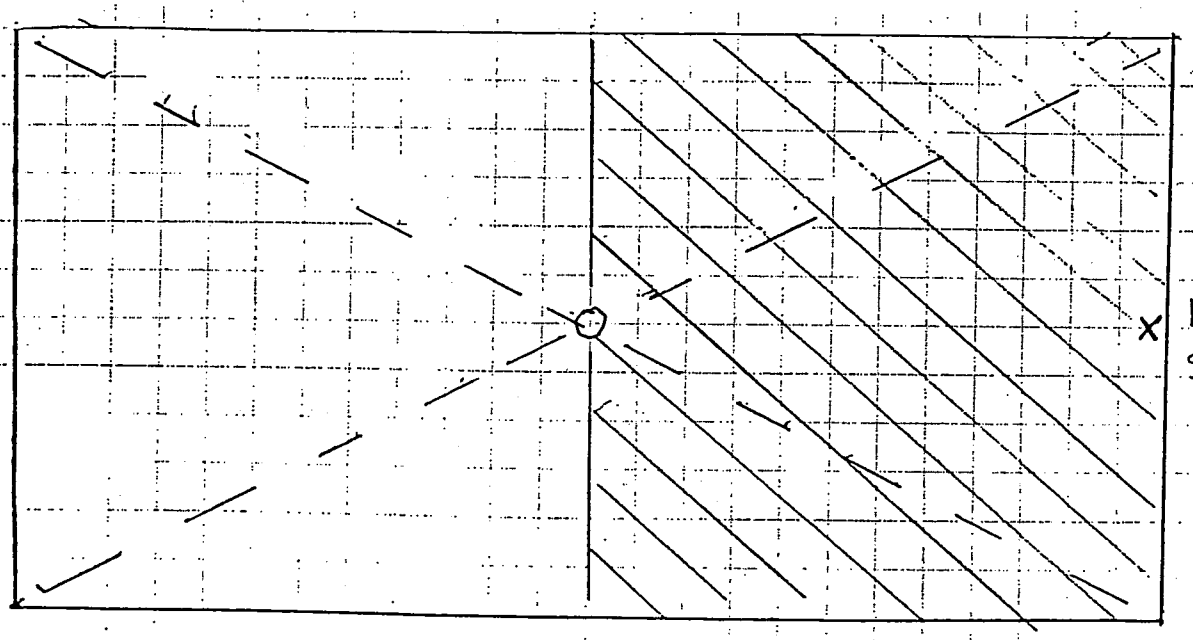

Figure 3: Worst-Case Aqueous Ammonia Release at Avenal: Ammonia Emission Rates as a Function of Time

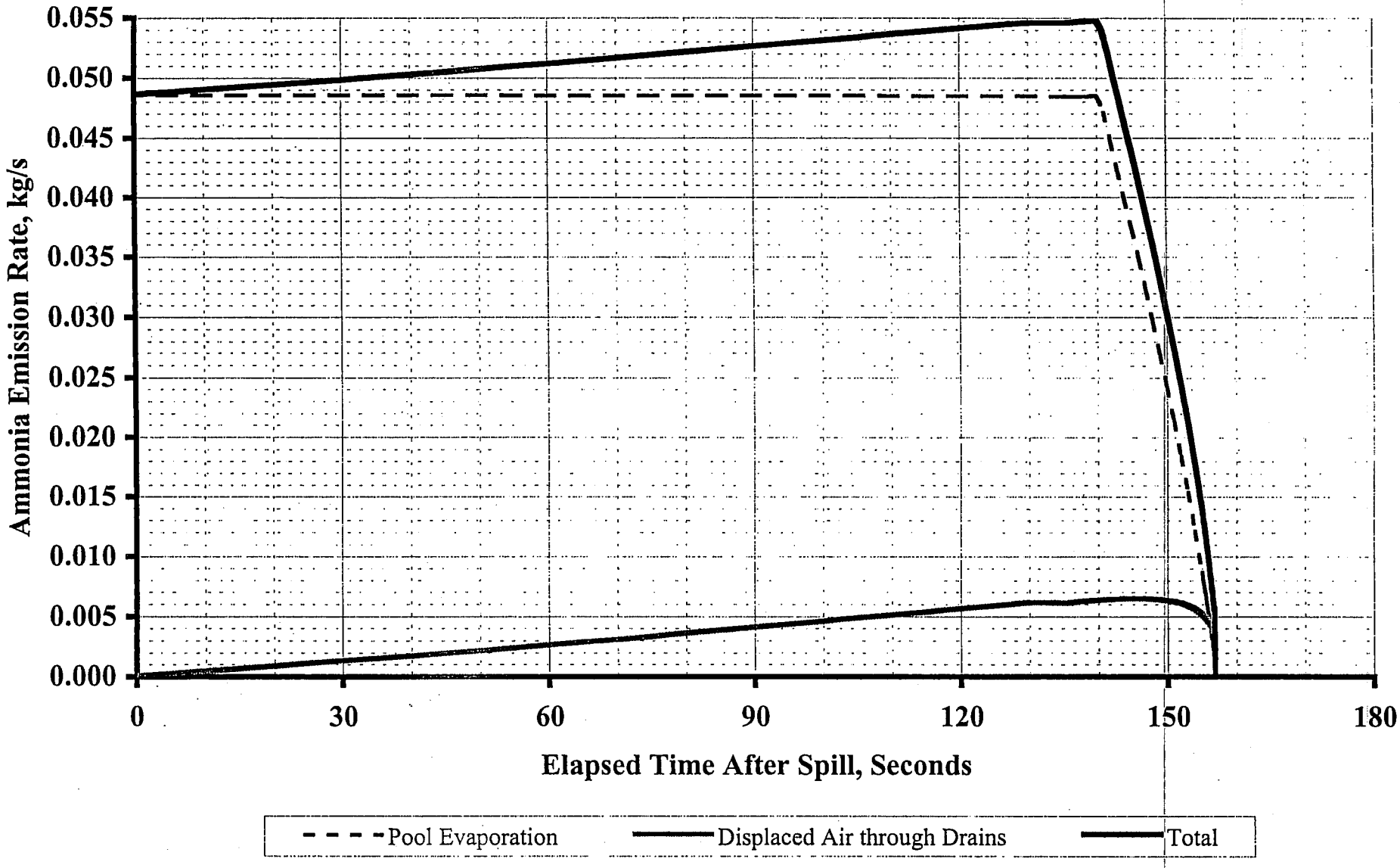
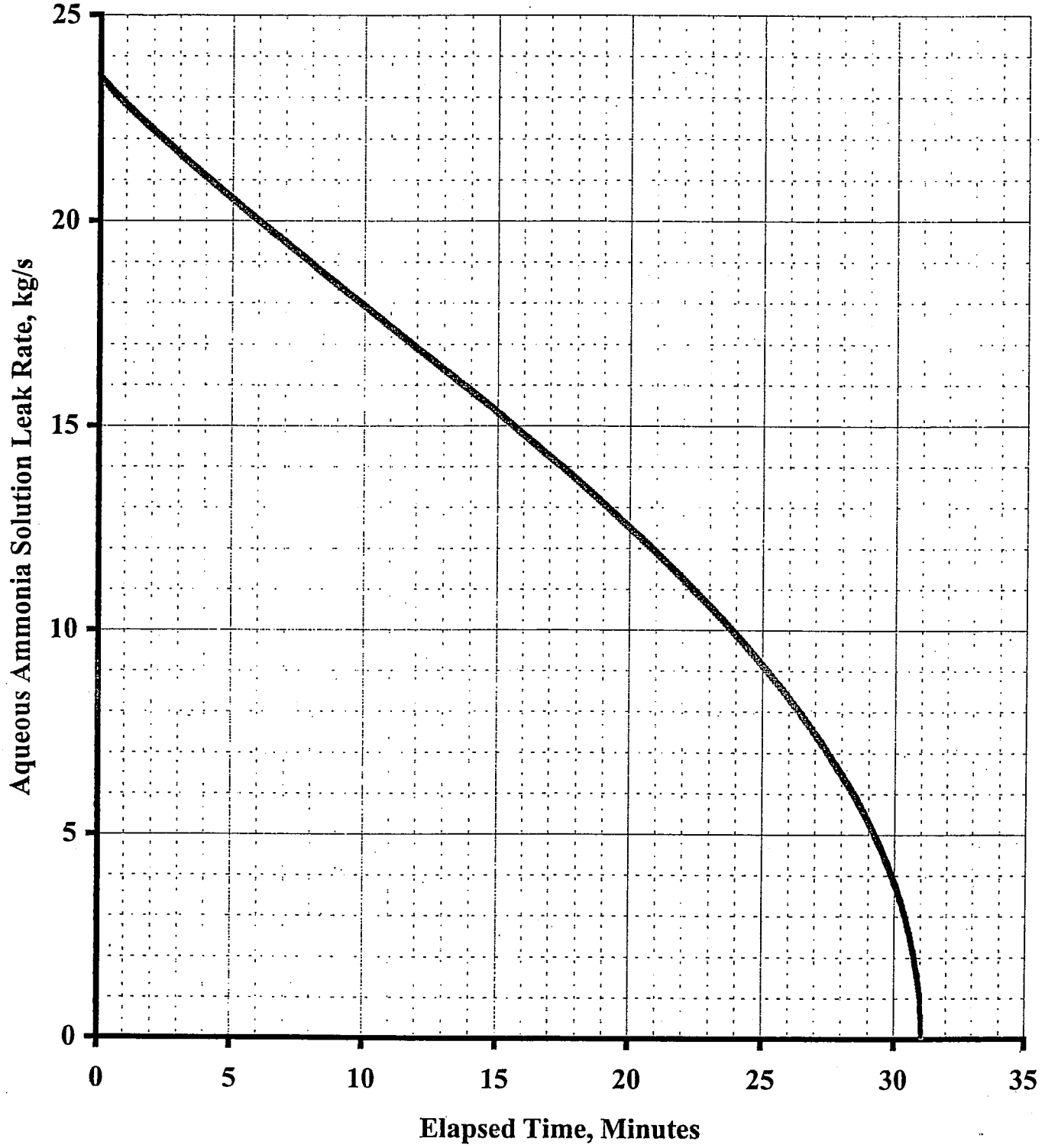
Figure 4:
Solution Leak Rate from 8,000-Gallon Tank Truck through 3-inch Hole as a Function of Time