

AN ABSTRACT OF THE THESIS OF

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ANIMAL WASTES

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A model to predict ammonia losses from sprinkler applied animal wastes was developed; in order to accomplish this, a review of literature was performed to determine possible methods of predicting ammonia losses during sprinkling. As adaptability to a large variety of situations was considered of maximum importance, the number of independent variables was amplified. Earlier literature provided a model of one droplet's ejection from a nozzle, flight, and evaporation. To this model were added equations predicting volatilization of ammonia during flight. Arguments were presented to support the expansion of losses from an "average" droplet for the system to describe losses for the entire system.

The resulting model predicted a sigmoidal variation of percent ammonia loss with pH, losses increasing rapidly between pH 8 and pH 10. Variation of loss with temperature was nearly linear, with slope increasing with increasing pH. The relationship of percent ammonia loss to droplet size, droplet velocity, nozzle height, and distance

travelled were also examined.

Ammonia losses from sprinkler applied lagoon effluent at the Oregon State University Swine Research Center were determined by analyzing ammonia concentrations in the waste before and after spraying. Resulting data were compared to the model's predictions. The effluent had a constant pH of 7, thus losses were small, but the analyzed percent loss matched the predictions within the limitations of the methods of analysis. Models and data from earlier studies were cited to support predictions at higher pH.

Modeling of Ammonia Losses in Sprinkler
Application of Animal Wastes

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MODELING OF AMMONIA LOSSES IN SPRINKLER
APPLICATION OF ANIMAL WASTES

INTRODUCTION

Disposal of animal waste effluents on pasture and crops is by now the most well-established method of controlling possible polluttional effects of the waste. Increased awareness of the potentials of nitrogen, both as a fertilizer and as a contaminant, has expanded present interest in its fate following land application. This plus the growth in size of livestock production enterprises has made precise knowledge of the quantity of ammonia nitrogen reaching the soil of vital interest.

Information exists on the amount of nitrogen in the raw wastes, as well as rough approximations of percentage loss expected for various handling methods. Only relatively recently has any real effort been made to model such losses in a form adaptable to a variety of real situations. One area in which predictions have been limited to broad estimates has been losses during sprinkling.

Research has been done on ammonia losses during spray application of liquid ammonia fertilizers, but most of this has been simple data collection and study of factors affecting losses. Since any predictions made were strictly empirical and based on a minimal consideration of variables, the applications of these studies are extremely limited.

The objectives of this study were to develop a model capable of predicting ammonia losses from sprinkler applied animal wastes. The model was designed to consider a large number of variables and to provide a more theoretical approach, thus increasing the reliability of the

predictions under a variety of conditions. Data were collected for a system with all variables noted, and the results compared to the predictions of the model. Lastly, the model's predictions were compared to the data of past studies to note similarities and differences.

REVIEW OF LITERATURE AND THEORY

In present-day agriculture, two problems moving toward a mutual solution are fertilization of crops and disposal of animal wastes. The latter has risen in magnitude as a problem of late, due mostly to the increase in large scale feeding operations. Disposal of wastes on land has always been the most popular alternative, but as animal production systems have increased in size to the realm of large business and industry, the precise methods of disposal, the cost, the land requirements, and the fertilizer value of waste have increased in importance.

Ammonia Losses from
Animal Wastes

Confinement facilities for animal production fall into two general categories: covered and open. The usual method of waste disposal in covered or housed feedlots (see Figure 1) includes 1) collection of wastes through slatted or sloped and guttered floors, 2) storage or treatment, and 3) land application of waste slurry, effluent, or solids (see Figure 2). Open feedlots (see Figure 3) generally use 1) removal of solids from the surface at intervals, 2) removal of storm runoff into a holding/treatment facility, and 3) spraying of liquids onto land (1).

Methods, cost and sizing for such facilities have been established (2). The land requirement for spraying has been determined based on nutrient concentration of wastes and an approximation of losses within the system (3). These losses have been estimated for various methods of collection and dispersal, based on collected data (3,4).

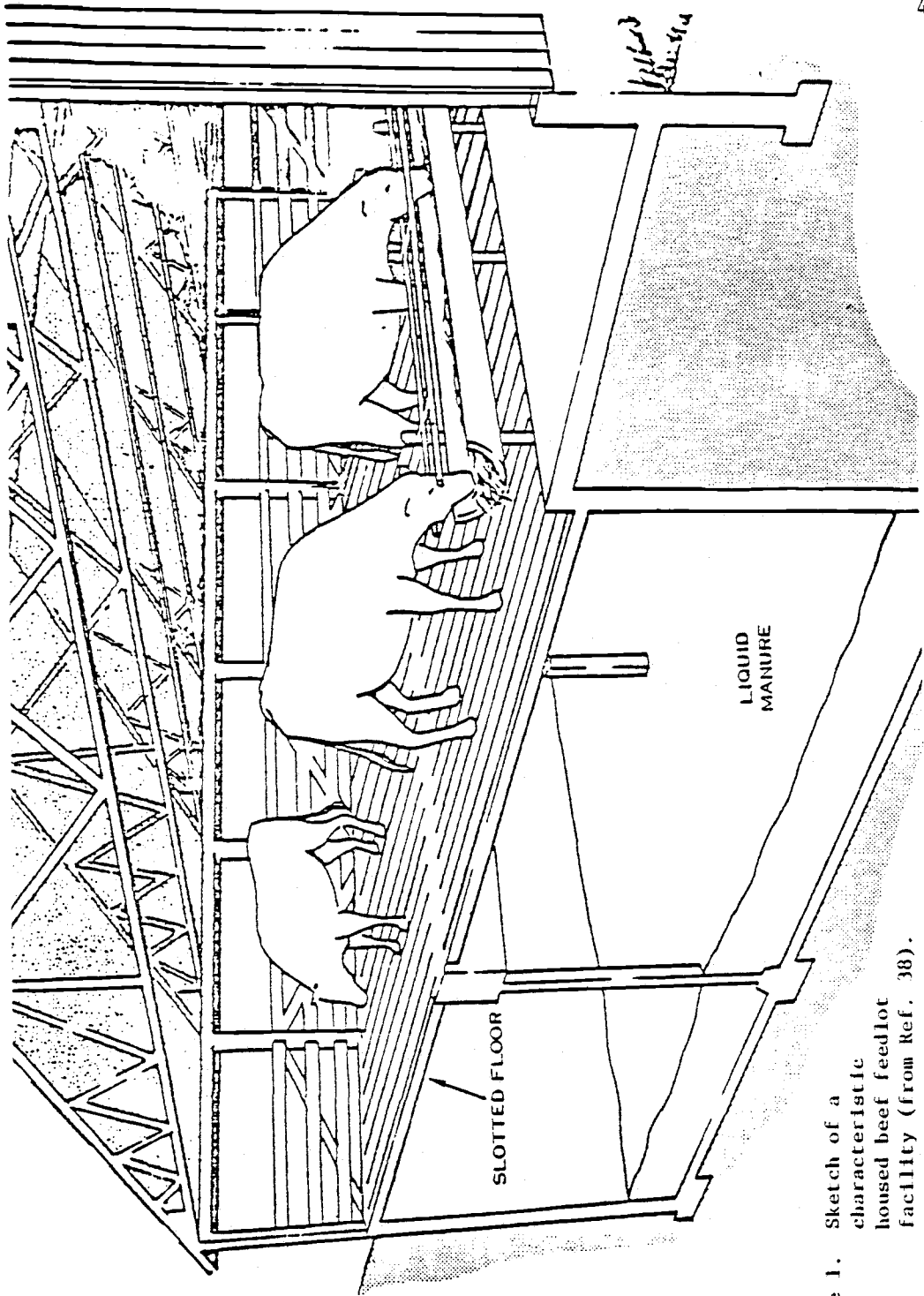
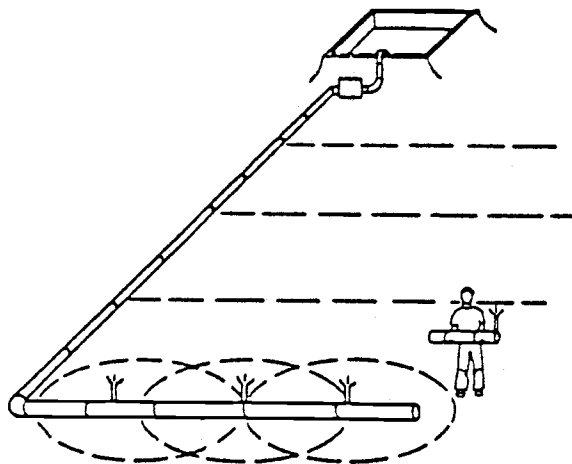
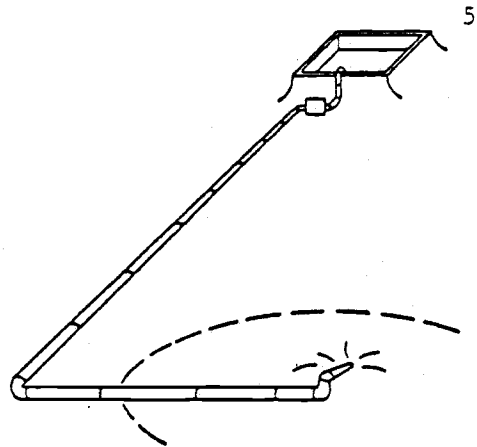


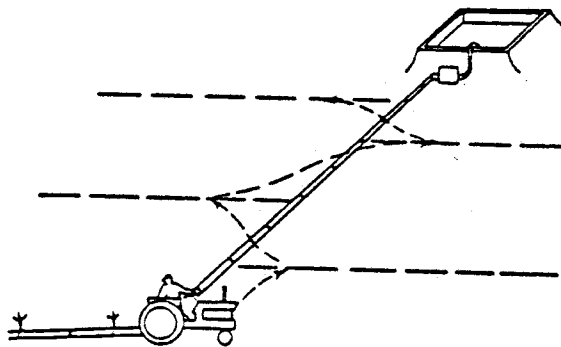
Figure 1. Sketch of a housed beef feedlot facility (from Ref. 38).



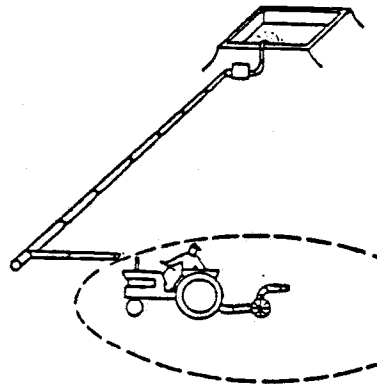
3a. Handmove system.



3b. Stationary big gun.



3c. Towline system.



3d. Towed big gun.

Figure 2. Popular methods of field spreading animal waste and affluent (from Ref. 38).

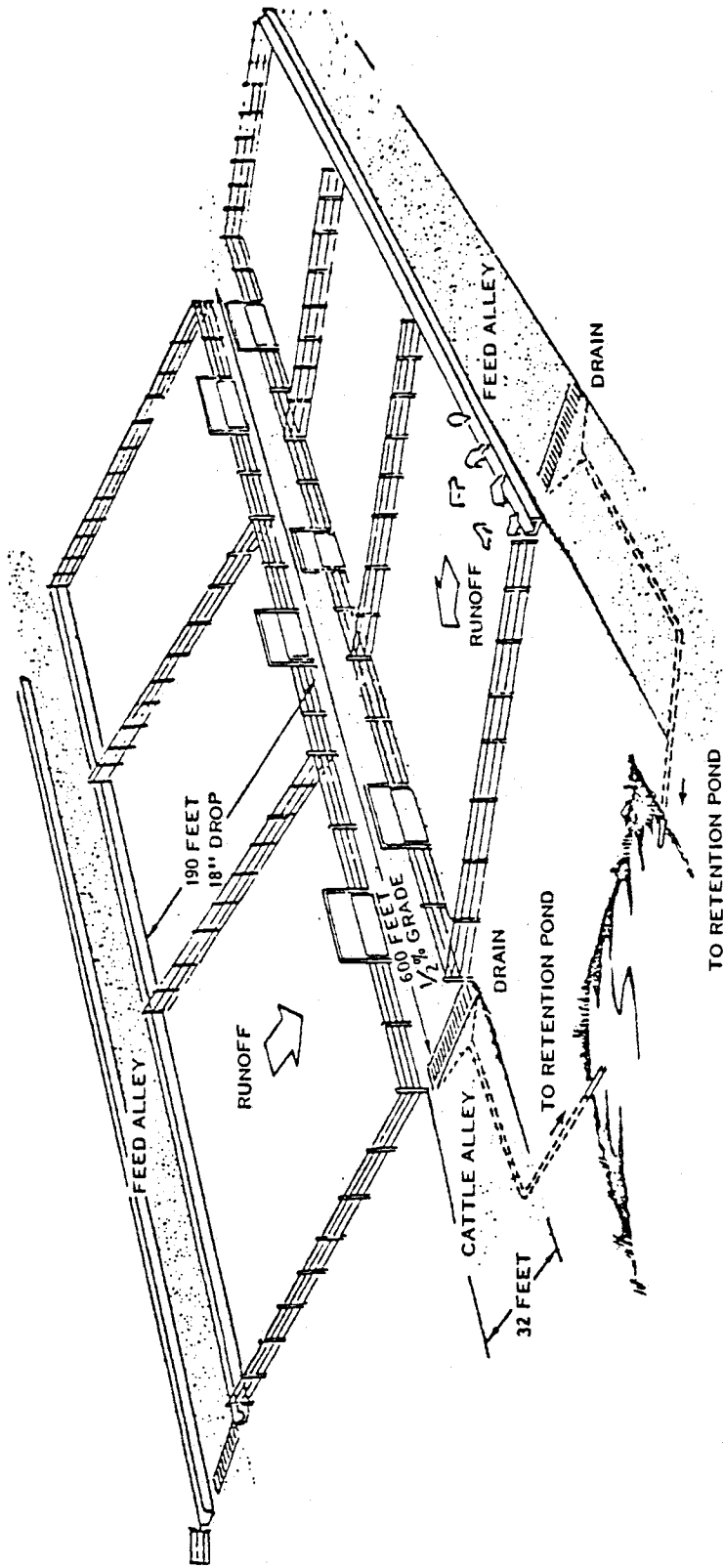


Figure 3. Sketch of a characteristic open beef feedlot facility (from Ref. 38).

The usual "limiting nutrient" has been nitrogen. The amount of cropland which can be adequately fertilized from a given waste disposal system is limited by the amount of nitrogen provided by the waste, and conversely, the amount of waste which can be disposed of on a given crop may be limited by the amount of nitrogen which the crop is able to utilize and remove. Nitrogen deficits can limit plant growth, excesses can cause ammonia toxicity and/or nitrates leaching into ground water (5).

Vanderholm (6) collected data to estimate the amount of nutrients, including nitrogen, left for various waste-handling systems (see Table 1). Generally, the methods which lost nitrogen most rapidly (had the least left) were those where there was exposure to air for long periods. Since these values were averages from a variety of geographical areas and a variety of long and short term weather conditions, their applicability to a specific case is questionable.

Miner (7) analyzed runoff from feedlots for nutrient value and pollutional potential, including nitrogen forms. He found ammonia nitrogen concentrations to range from 50-139 mg/l during the summer, 20-77 mg/l during the fall and 1.3-1.7 mg/l during the winter for surfaced lots; ammonia concentrations from unsurfaced lots were somewhat lower. He explained the variation as due to changing metabolic activity, with temperature, of the organisms which break down urea and proteins. Although ammonia can be bacterially oxidized to nitrites and nitrates, this did not occur. Existing biological activity kept the feedlot surface anaerobic, and the absence of dissolved oxygen prevented such oxidation.

Handling and disposal method	Swine			Beef			Dairy			Broiler			Layer			Turkey		
	N	P ₂ O ₅	K ₂ O	N	P ₂ O ₅	K ₂ O	N	P ₂ O ₅	K ₂ O	N	P ₂ O ₅	K ₂ O	N	P ₂ O ₅	K ₂ O	N	P ₂ O ₅	K ₂ O
	Fertilizer content, lb/1000 lb liveweight																	
Manure pack																		
Broadcast	84	107	124	63	77	99	77	50	112	215	200	149	135	202	129	168	204	195
Broadcast and cultivation	102	107	124	77	77	99	91	50	112	263	200	149	102	202	129	202	204	195
Daily scrape																		
Broadcast	-	-	-	-	-	-	89	52	104	-	-	-	155	202	123	-	-	-
Broadcast and cultivation	-	-	-	-	-	-	106	52	104	-	-	-	188	202	123	-	-	-
Open lot																		
Broadcast	58	61	80	44	45	64	51	30	59	-	-	-	-	-	-	117	120	104
Broadcast and cultivation	70	61	80	53	45	64	61	30	59	-	-	-	-	-	-	141	120	104
Deep pit																		
Broadcast	-	-	-	-	-	-	-	-	-	-	-	-	164	209	123	-	-	-
Broadcast and cultivation	-	-	-	-	-	-	-	-	-	-	-	-	201	209	123	-	-	-
Manure pit																		
Broadcast	95	111	119	69	82	95	87	54	107	-	-	-	-	-	-	-	-	-
Knifing	124	111	119	94	82	95	114	54	107	-	-	-	-	-	-	-	-	-
Irrigation	92	93	99	65	82	95	84	45	89	-	-	-	-	-	-	-	-	-
Lagoon																		
Irrigation	24	25	89	18	18	71	23	14	80	-	-	-	-	-	-	-	-	-

Table 1. Annual fertilizer content, approximate. Nutrients available after losses due to handling and storage. To convert P₂O₅ to elemental P, multiply by 0.44. To convert K₂O to elemental K, multiply by 0.83 (from Ref. 2). Dashed lines refer to example.

Koelliker and Miner (8) examined the losses of ammonia nitrogen from an anaerobic swine waste lagoon. First they examined the equilibrium between ammonia and ammonium ion to determine the actual amount of nitrogen available for loss by volatilization. Using the dissociation constant for the ammonia-ammonium ion equilibrium they showed that for the reaction:



$$K_b = \frac{[\text{NH}_4^+][\text{OH}^-]}{[\text{NH}_3][\text{H}_2\text{O}]} \quad [2]$$

Where K_b = the dissociation constant of ammonia

$[\text{NH}_4^+]$ = the concentration of ammonium ion (mols/l)

$[\text{OH}^-]$ = the concentration of hydroxide ion (mols/l)

$[\text{NH}_3]$ = the concentration of ammonia (mols/l)

$[\text{H}_2\text{O}]$ = the concentration of water: considered equal to unity

or

$$[\text{NH}_3\text{-N}] = \frac{K_w}{K_b} \frac{[\text{NH}_4^+\text{-N}]}{[\text{H}^+]} \quad [3]$$

Where K_w = the dissociation constant of water and, taking negative logs,

$$[\text{NH}_3\text{-N}] = 10^{(\text{p}K_b + \text{pH} - \text{p}K_w)} [\text{NH}_4^+\text{-N}] \quad [4]$$

Using this equation plus changes in the value of $\text{p}K_b$ and $\text{p}K_w$ with temperature generated the graph in Figure 4.

They then modeled this mass transfer of ammonia from the lagoon surface according to the equation:

$$\frac{d(\text{NH}_3\text{-N})}{dt} = A K (P_i - P_g) \quad [5]$$

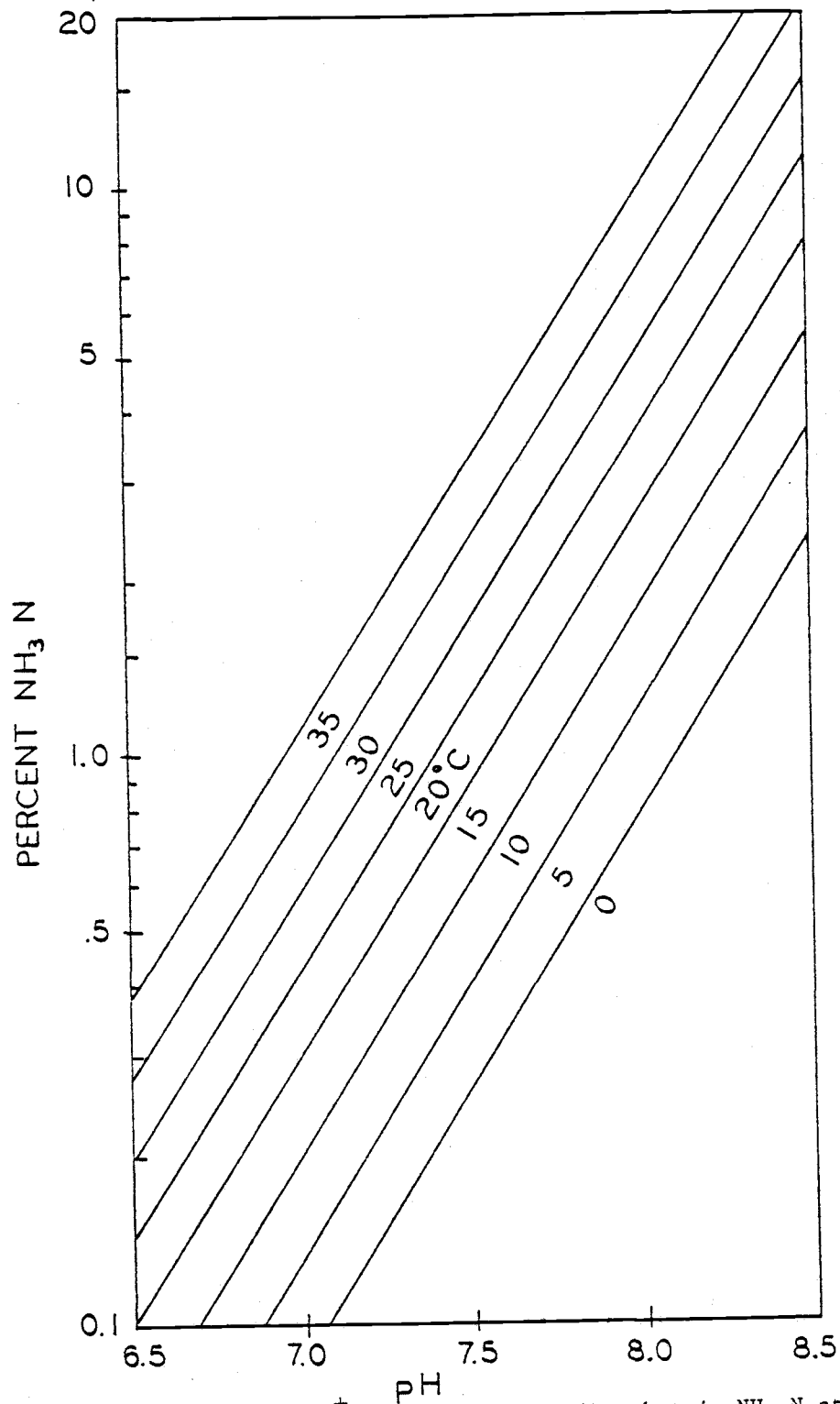


Figure 4. Percentage of $\text{NH}_4^+ + \text{NH}_3\text{-N}$ in solution that is $\text{NH}_3\text{-N}$ at equilibrium at various expected conditions in an anaerobic manure lagoon (from Ref. 8).

Where $\text{NH}_3\text{-N}$ = the ammonia nitrogen transferred (lb)

t = time (d)

A = surface area (ft^2)

P_1 = partial pressure of $\text{NH}_3\text{-N}$ in liquid (atm)

P_g = partial pressure of $\text{NH}_3\text{-N}$ in air (atm)

K = overall transfer coefficient ($\text{lb/d}\cdot\text{ft}^2\cdot\text{atm}$)

Their study endeavored to predict losses by measuring P_g near the lagoon, using A equal to the area of the lagoon surface, and P_1 from measurement and previous pH considerations. K was evaluated by Halsam's equation that:

$$K = 2.6 \times 10^5 V^{0.8} T^{1.4} \quad [6]$$

Where V = gas velocity (ft/sec)

T = temperature ($^{\circ}\text{K}$)

Ammonia Losses from Sprayed Aqueous Solution

Various people have examined losses of ammonia during sprinkling of liquid fertilizers. Henderson, Bianchi and Doreen (9) sprayed aqua ammonia, ammonium phosphate, and ammonium nitrate on a gridded field. Losses were examined and curves developed predicting percent ammonia lost with increasing concentrations of ammonia and the various ammonium salts. While the curves of percent loss versus concentration varied according to the ammonia form being considered (see Figures 5 and 6) the various curves can be combined into a single curve for the graph of percent ammonia loss versus pH (see Figure 7). Henderson, Bianchi and Doreen also suggested that percent ammonia loss should be related in some way to temperature variations.

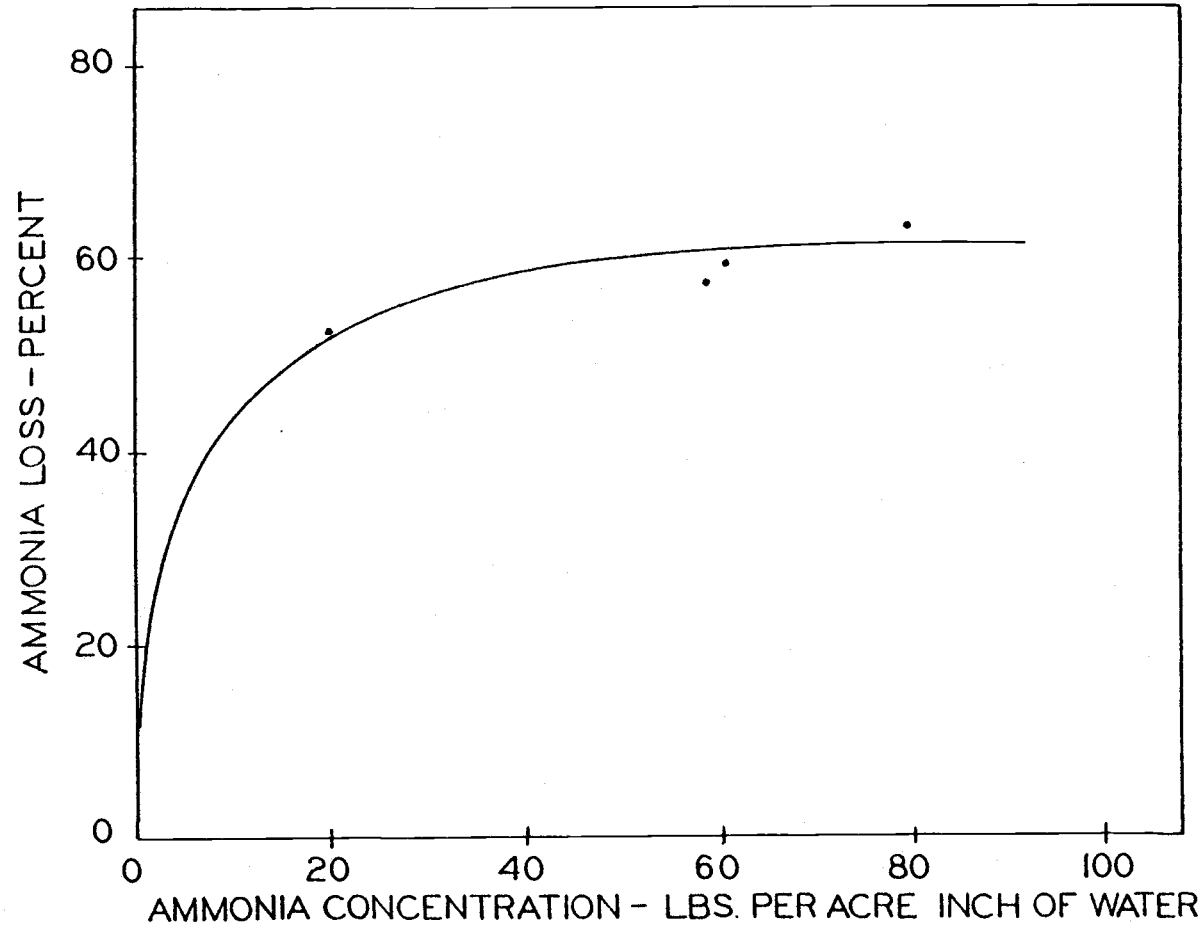


Figure 5. Losses of aqua ammonia in relation to concentration of ammonia in irrigation water (from Ref. 8).

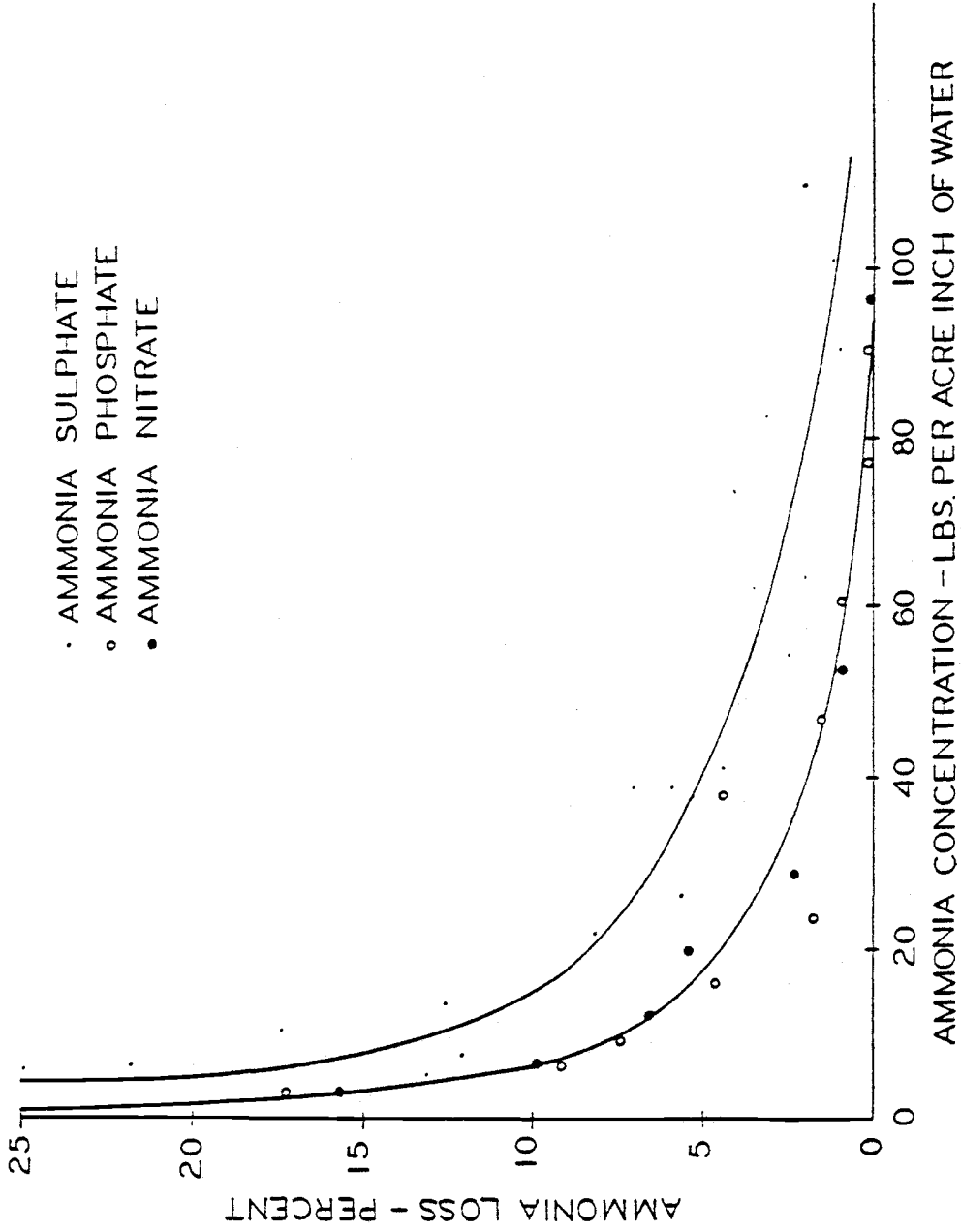


Figure 6. Losses of ammonia from fertilizer salts in relation to ammonia concentration in the irrigation water (from Ref. 9).

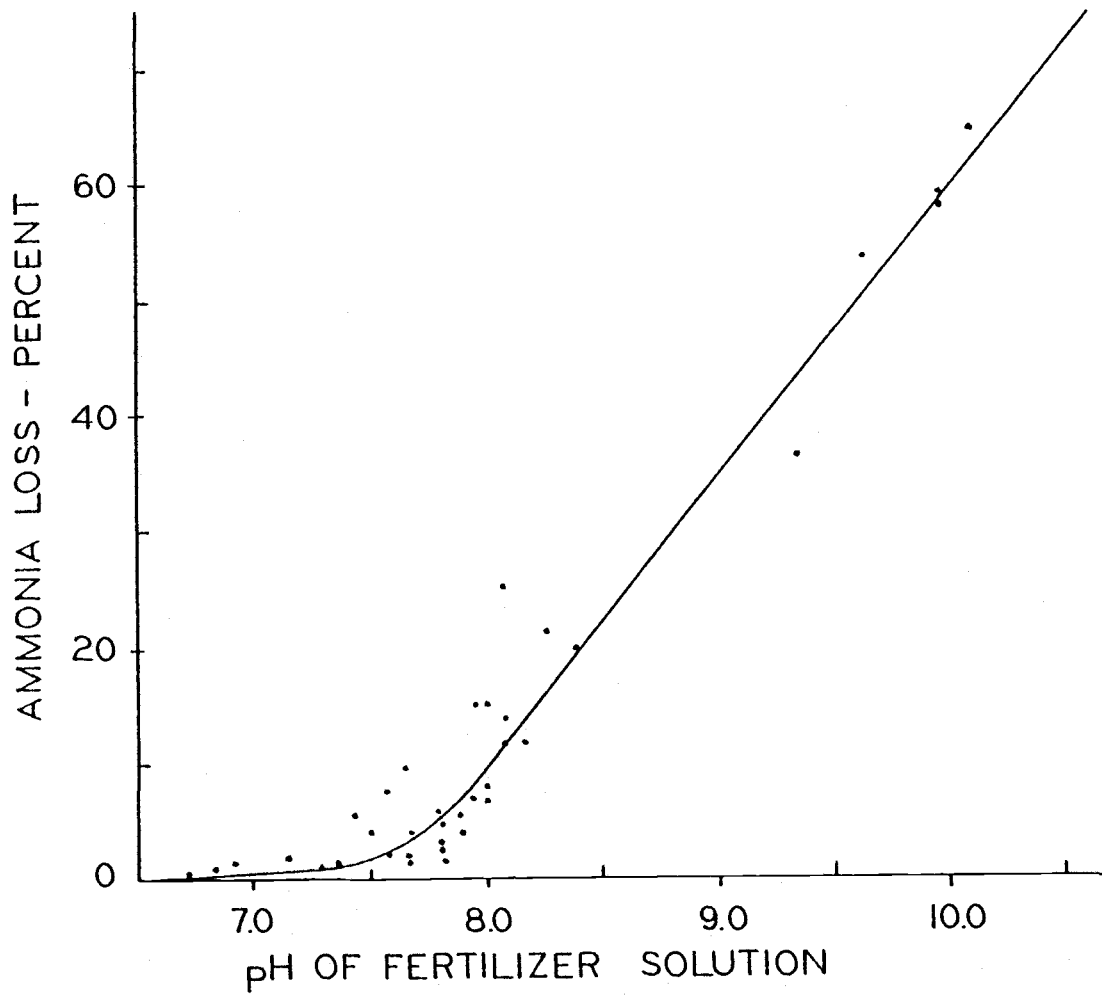


Figure 7. Losses of ammonia from aqua ammonia and ammonium salts in relation to the pH of the fertilizer solution (from Ref. 9).

Miyamoto (10) examined optimum pH and concentrations for sprayed ammonia fertilizers and the feasibility of reaching the desired pH by addition of acid. His study of ammonia losses with increasing pH closely paralleled that of Henderson, et al. (9). A pH of 7.5 or below gave insignificant losses.

Jackson, Alban, and Wolfe (11) examined the losses of ammonia during spraying of ammonia solutions with variables of distance sprayed, concentration of ammonia, initial temperature of the water, and pH. Losses with concentration and water temperature were matched with curves which showed an increase in ammonia loss with an increase in either (see Figure 8). In addition, data showed increased losses with increased pH and distance sprayed.

All of these investigators noted that there will be some evaporation of ammonia after the droplet has struck. Although some considered this loss to be large, none attempted to quantify it in any way. Some assumed such losses to be negligible.

Roessler, et al (12) (1971) examined the rate of ammonia loss in the ammonia stripping process, using an "ammonia transfer unit height", the distance over which a certain amount of ammonia is lost, in their case, the height in feet which the spray must fall to lose a pound mole of nitrogen per cubic foot of spray. This height varied according to the system used, and was calculated from collected data for wood-slat-packed stripping towers.

This model began with a mass balance for ammonia in the tower, so that air flow rate multiplied by change in concentration of ammonia in air equals liquid flow rate times change in concentration of ammonia in

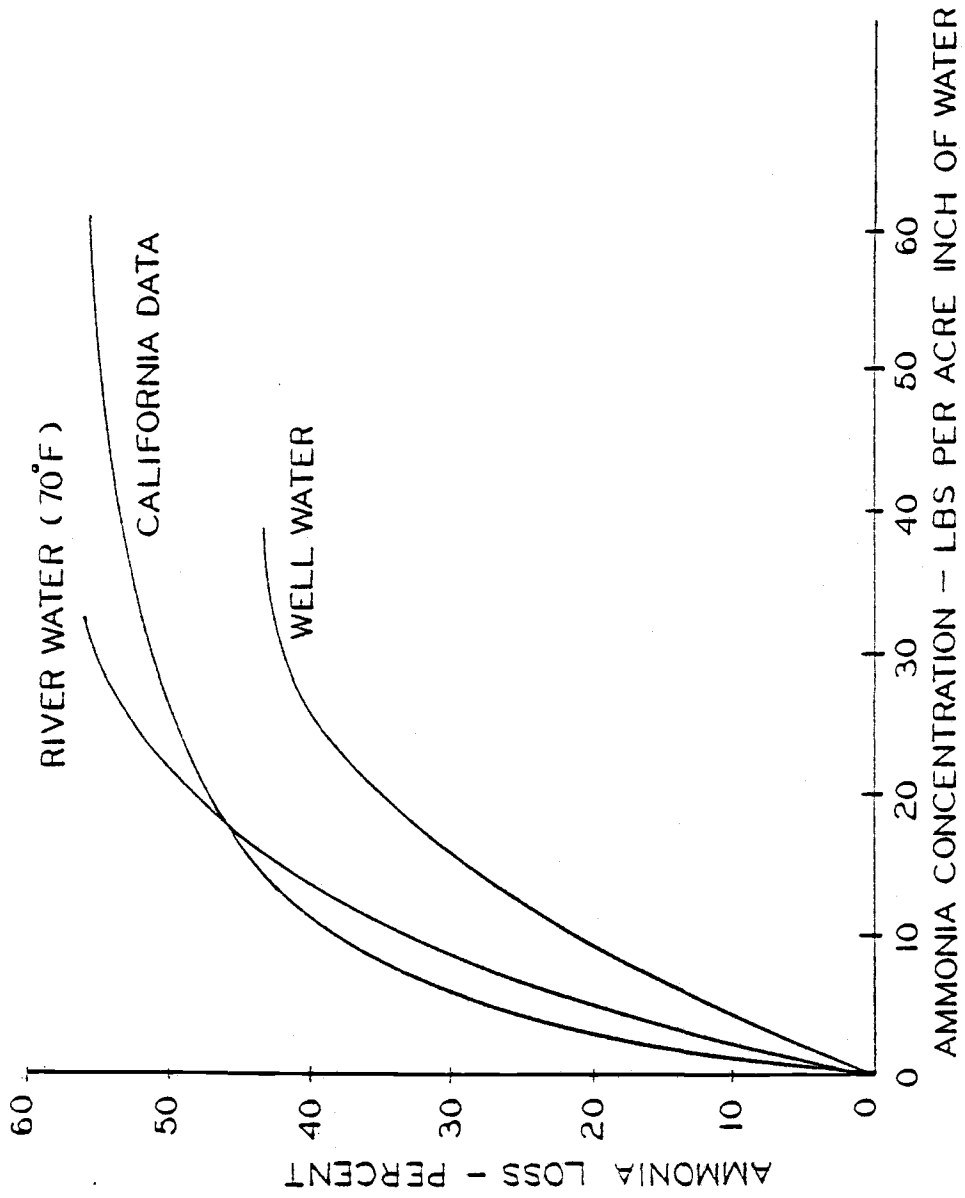


Figure 8. Effect of water temperature and ammonia concentration on Nitrogen losses (from Ref. 11).

water. This was added to a similar analysis of heat transfer and thus cooling in the tower to calculate the change in Henry's Law Constant, according to the empirical relation

$$K_H = 0.1117 e^{0.02612T} \quad [7]$$

Where K_H = Henry's Law Constant (dimensionless)

T = temperature ($^{\circ}$ F)

Also, empirical relationships were developed for predicting pressure changes and systems' costs.

Forces Acting on a Droplet

For the purpose of developing a predictive model for the loss of ammonia in sprinkling, the most logical approach seemed to be modelling the losses from a single droplet shot from a sprinkler, and expanding losses from the "average droplet" for the system to calculate losses for the entire sprinkler and sprinkler system.

Welty, Wicks, and Wilson (13) described the forces acting on a single droplet. The droplet, once launched tends to decrease in speed due to drag force, and to increase in speed (or decrease, depending on direction of launch) due to gravity. Since the droplet is evaporating and velocity is changing, the drag force is continually being altered at a varying rate. The changing drag force, in turn, alters the rate of change of velocity. Likewise, the change in velocity and the change in surface area will affect the rate of evaporation. One of the major obstacles to the project was describing all of these variables in order to predict ammonia losses. The modes of ammonia loss would be similar in

nature to those of water loss, but would have to include a concentration factor, since volatilization of ammonia would tend to decrease concentration and, thereby, rate of ammonia loss, while decreasing droplet size would tend to increase both.

Frost and Schwalen (14) studied water losses from sprinkler systems and constructed a nomograph for estimating water losses. Variables in the nomograph include humidity, air temperature, nozzle diameter and wind velocity (see Figure 9). The nomograph was based on data collected in various geographic areas, the data being grouped according to the five variables and averaged within groups. A computer was then used to develop the included nomograph. Some of their conclusions were as follows:

1) Evaporation losses on humid, windless, cool days averaged about 3 percent, while losses on humid, windless, hot days averaged about 10 percent.

2) Raising the nozzle pressure from 30 psi to 50 psi increased losses, and the difference increased as temperature rose and humidity dropped.

3) At high wind velocities losses increased due to droplets being carried outside the testing area. Since this "wind drift" did not noticeably moisten the ground, it was counted as a total loss. Doubling the wind velocity doubled the losses.

4) Losses increase with temperature, wind velocity, operating pressure and degree of breaking of spray and decrease with increase in humidity and nozzle diameter. They are most directly related to vapor pressure deficit which is a function of temperature and relative humidity.

Frost and Schwalen's concept of "wind drift" creates a dilemma in

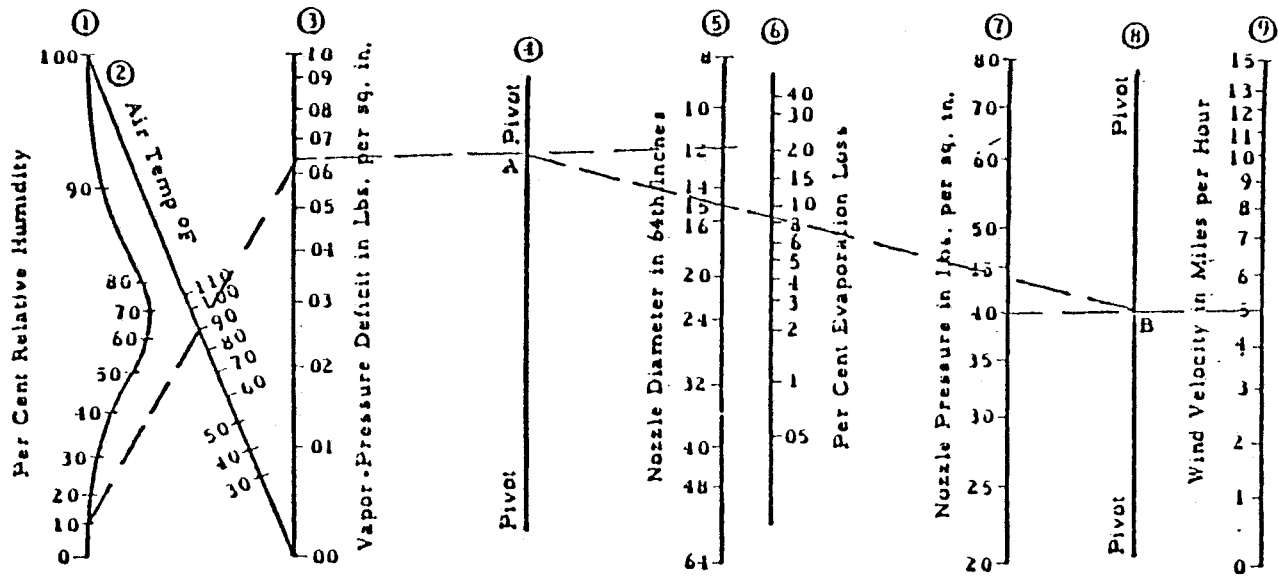


Figure 9. Nomograph for determining the spray and wind drift losses for specific weather conditions, nozzle size and pressures (from Ref. 14).

modelling. Although the spray does not fall on the test plot, it does fall somewhere, and with a field significantly larger than the test plot, most will end up on the irrigated field. Likewise, whatever ammonia is dissolved in it will reach the field, if not diffused into the air first. Even if the assumption that water contributions to the field from wind drift is negligible holds true, the same is not necessarily acceptable for ammonia.

Since the system was empirically derived, there is no way to treat various parts of the spray separately. Therefore, unless one assumes that ammonia loss is directly related to water loss, the nomograph does not lend itself to use for calculation of vaporized ammonia.

Seginer (15) modelled water losses during sprinkling based on a description of the forces involved as conductances and resistances yielding a net mass transfer. The model begins by assuming that a standard situation in which losses are non-existent can be approximated by operating during a calm, cool night. Losses in other situations are compared to this case.

Possible water losses were then broken down into three subcategories: 1) spray evaporation from the droplets, 2) surface evaporation after droplet impact, and 3) drift losses or "wind drift".

In each evaporation case, loss rates were described via the conductance to an intermediary point (the spray level) and then a total conductance into the atmosphere well above the field. Conductance was defined such that

$$S = \rho C_s (q_s - q) \quad [8]$$

$$\text{and } A = \rho C_a (q_a - q) \quad [9]$$

$$\text{and } S + A = \rho C_t (q - q_r) \quad [10]$$

where

S = spray evaporation ($\text{g}/\text{cm}^2\text{S}$)

A = surface evaporation ($\text{g}/\text{cm}^2\text{S}$)

ρ = density of the fluid (g/cm^3)

C_s = conductance for vapor transfer between spray and air
(cm/S)

C_a = conductance for vapor transfer between wet surface and
air (cm/S)

C_t = conductance for vapor transfer from spray level upward
(cm/S)

q_s = specific humidity at spray (dimensionless)

q_a = specific humidity at spray droplet surface (dimensionless)

q_s = specific humidity at wet surface (dimensionless)

q = specific humidity at spray level (dimensionless)

q_t = specific humidity at upper level (Z_T) (dimensionless)

(see Figure 10)

Seginer then analyzed the conductances, finding

$$C_a = \frac{k u^*}{\ln\left(\frac{Z_s}{Z_o}\right)} \quad [11]$$

$$C_t = \frac{k u^*}{\ln\left(\frac{Z_t}{Z_s}\right)} \quad [12]$$

where k = von Karman constant (dimensionless)

u^* = friction velocity (cm/s)

Z_s = level representative of spray (cm)

Z_T = level where variation in application does not affect specific humidity (cm)

Z_o = ground level (cm)

For the spray,

$$C_s = \frac{R \bar{h} \bar{t}}{P C_p \bar{d}} \quad [13]$$

Where R = application rate (cm/S)

\bar{h} = average value of heat transfer coefficient (cal/S·cm³·°C)

P = density of fluid (g/cm³)

C_p = heat capacity (at constant pressure) of the fluid (cal/g°C)

\bar{d} = average diameter of droplet (cm)

\bar{t} = average length of time the droplet travels (sec)

For the drift, it was assumed that in a large, homogeneous field, there would essentially be no losses, since fine spray would eventually descend within the field. It was also noted that although possible drift losses cannot be described by energy balances, these losses will be directly proportional to rate of application, so that graphically, spray, surface, and wind drift losses can be shown as in Figure 10.

Experimentation centered around variation of water losses with solar intensity, with the assumption that temperature, humidity, and wind speed variation correlate closely with solar intensity changes. For this case such an assumption was justified, since the research was done in Israel, where there is very little variation in summer weather from day to day.

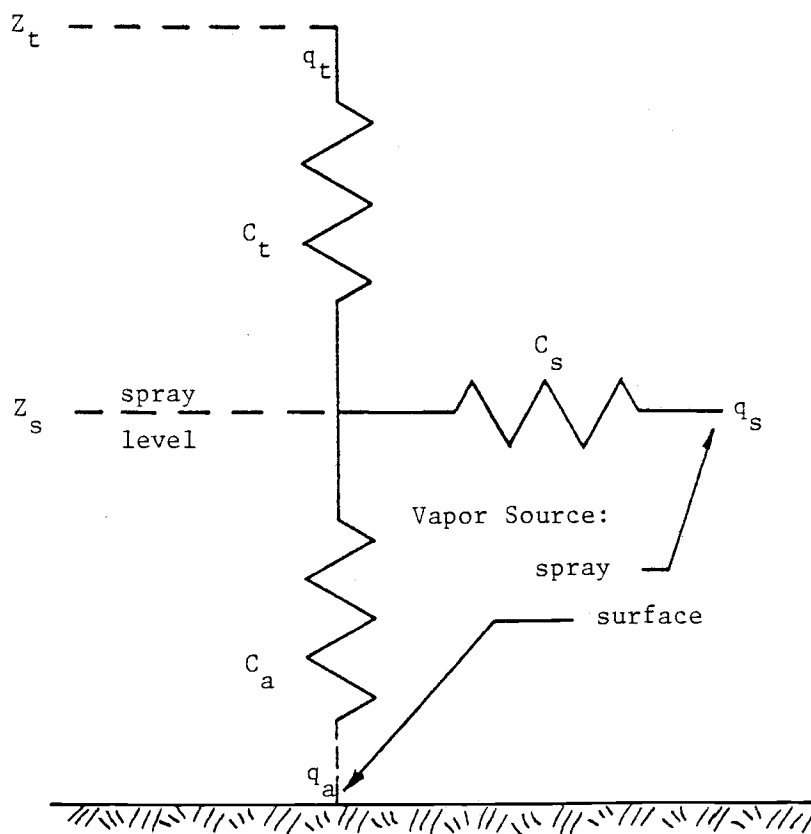


Figure 10. A resistance model of evaporation during sprinkling (from Ref. 15).

Finally, Goering, Bode and Gebhart (16) modelled a single droplet launched and the forces acting on it, and developed a computer program to simulate the resulting trajectory and evaporation losses. As this model and program were of extreme importance to the investigation, what follows will develop the model, reviewing pertinent background literature.

In 1924 Lewis and Whitman (17) proposed that mass transfer between gas and liquid phases required passage through two films at the interface. Rate of mass transfer is dependent upon the resistance of those two films, which Lewis and Whitman theorized could be added for total resistance. More recently, investigators have proven that a resistance exists at the interface itself if dust or other foreign particles are carried by the liquid. However, the two-resistance theory is still most commonly used, particularly for interpreting, and making predictions from industrial data.

Since, according to Fick's first law, the flux of a substance through a plane perpendicular to the direction of diffusion is directly proportional to the concentration gradient, the molar flux can be expressed by

$$N_{A,l} = k_g (P_{A,g} - P_{A,i}) \quad [14]$$

$$\text{and } N_{A,g} = k_l (C_{A,g} - C_{A,i}) \quad [15]$$

Where

$$N_{A,g} = \text{rate of diffusion of component A on the gaseous side of the interface (mole/s}\cdot\text{m}^2)$$

$N_{A,1}$ = rate of diffusion of component A on the liquid side of the interface (mols/s·m²)

k_g = convective mass transfer coefficient for diffusion of vapor through a second, non-diffusing component.

k_l = convective mass transfer coefficient for diffusion of liquid through a second, non-diffusing component.

$P_{A,g}$ = partial pressure of component A in the bulk gas phase (Pa)

$P_{A,i}$ = partial pressure of component A at the interface (Pa)

$C_{A,i}$ = concentration of component A at the interface (moles/m³)

$C_{A,l}$ = concentration of component A in the bulk liquid phase (moles/m³)

At the interface, $P_{A,i}$ and $C_{A,i}$ are related according to Henry's Law, just as at equilibrium, that is

$$P_A = H C_A \quad [16]$$

Where H = Henry's Law constant (Pa/ $\frac{\text{mol}}{\text{m}^3}$)

See Figure 11 for a graphical representation.

For a falling droplet of pure water, there is no concentration gradient within the liquid phase, therefore diffusion from the droplet can be described by Equation [14] alone.

In their study of evaporation of droplets in connection with spray drying, Ranz and Marshall (18) used Equation [14], but multiplied by the surface area of the droplet (assumed spherical) and the molecular weight of water, so that

$$\frac{dm}{dt} = k_g A_s \Delta P M_v \quad [17]$$

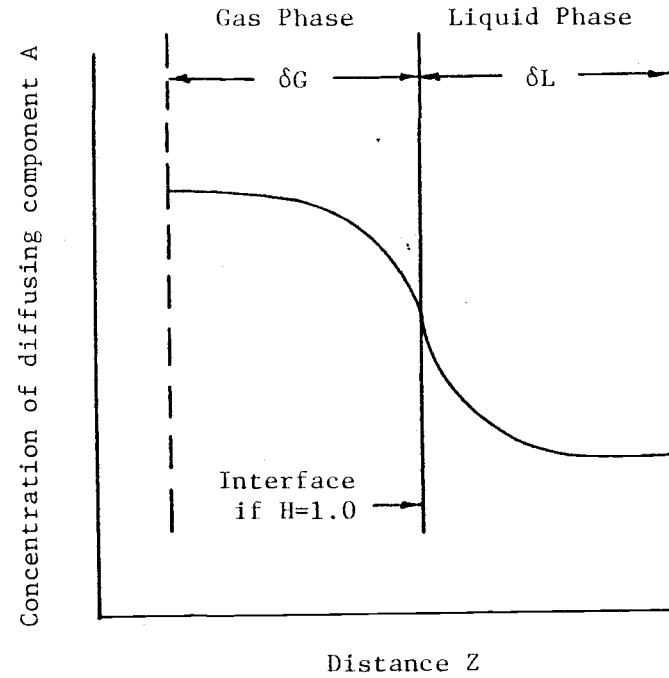
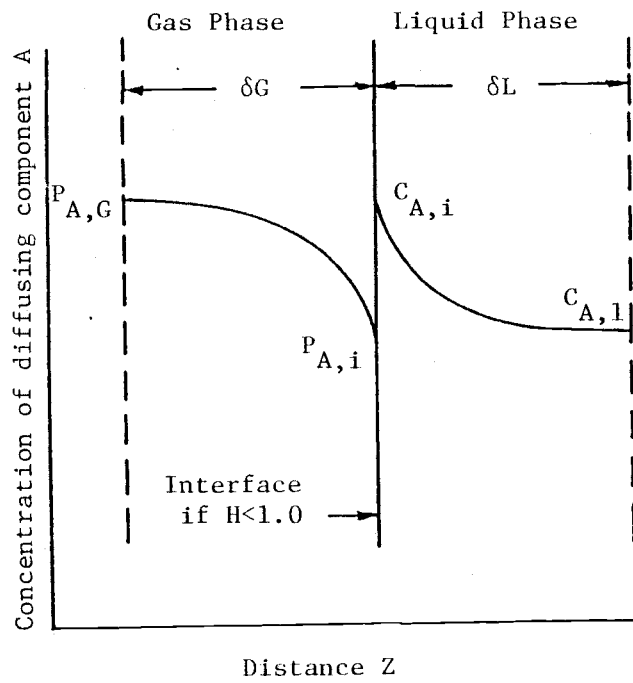


Figure 11. Concentration gradients between two contacting phases (from Ref. 13).

$\frac{dm}{dt}$ = rate of mass transfer (g/s)

A_s = surface area of the droplet

ΔP = vapor pressure difference (between droplet surface and bulk air)

The equation is basically the same as that employed by Koelliker and Miner (8) (Eq. 5). However, the approach to finding the value of K_g differed.

Through Nusselt's work in energy transfer, use of a dimensionless number (called a Nusselt number) characteristic of fluids and their convective and conductive thermal resistances developed. In the analogous case in mass transfer, the mass transfer Nusselt number or Sherwood number, as it is sometimes known, is evaluated as

$$Nu_{AB} = \frac{k_c L}{D_{AB}} \quad [18]$$

Where

Nu_{AB} = the mass transfer Nusselt number for a system of components A and B (dimensionless)

k_c = convective mass transfer coefficient $\left(\frac{\text{mols}}{\text{m}^2 \cdot \text{s} \cdot \text{mols/m}^3}\right)$

L = length (in)

D_{AB} = mass diffusivity or diffusion coefficient for component A diffusing through component B (m^2/s)

Later investigators (13) found the Nusselt number for a sphere to vary in the form

$$Nu_{AB} = Nu_{AB0} + CRe^{1/2} Sc^{1/3} \quad [19]$$

Where

Nu_{AB0} = the Nusselt number at very low Reynold's number;
 $Nu_{AB0} = 2.0$ (dimensionless)

C = correlating constant (dimensionless)

Re = Reynold's number; $Re = \frac{LV}{\nu}$ (dimensionless)

Where V = velocity (m/s)

ν = kinematic viscosity (m^2/s)

Sc = Schmidt number; $Sc = \frac{\mu}{\rho D_{AB}}$ (dimensionless)

Where μ = viscosity (Pa·s)

ρ = density (kg/m^3)

Frössling¹ found that for this system, C equals 0.552. Later studies by Ranz (18) adjusted the value to 0.5, so that the equation becomes

$$\frac{k_c D}{D_{AB}} = 2.0 + 0.6 Re^{1/2} Sc^{1/3} \quad [20]$$

Marshall (20) used this equation for the evaporating droplet, and multiplied by factor of

$$\frac{\rho_a}{M_m p_f}$$

Where ρ_a = density of air (g/cm^3)

M_m = mean molecular weight of gas mixture in transfer path (g/mol)

p_f = partial pressure of air ($dynes/cm^2$)

This factor changes k_c to k_g and the units from $\frac{moles}{m^2 \cdot s \cdot \frac{mols}{m^3}}$

¹N. Frössling, Gerlands Beitr. Geophys., 52, 170 (1938) quoted by reference 13.

to $\frac{(\text{moles})}{\text{m}^2 \cdot \text{s} \cdot \text{Pa}}$, so that the equation becomes tailored to a vapor sys-

tem. The equation for k_g is now

$$k_g = \frac{D_{AB} \rho_A}{M_m D_p P_f} [2.0 + 0.6 \text{Re}^{1/2} \text{Sc}^{1/3}] \quad [21]$$

Since droplets are assumed spherical, the surface area of the droplets is

$$A_s = \pi D_p^2 \quad [22]$$

$$\text{and } m = \rho_1 \pi \frac{D_p^3}{6} \quad [23]$$

where ρ_1 = density of the liquid (kg/m^3)

The mass transfer rate now becomes

$$\frac{dm}{dt} = \rho_1 \pi \frac{D_p^2}{2} \frac{dD_p}{dt} \quad [24]$$

and

$$\frac{dD_p}{dt} = -2 \frac{M_v D_v \rho_A \Delta p}{M_m D_p \rho_1 P_f} (2.0 + 0.6 \text{Re}^{1/2} \text{Sc}^{1/3}) \quad [25]$$

for steady state evaporation from a droplet.

Ranz (18) evaluated D_v for an air-water system as

$$D_v = 5.28 \times 10^{-6} T_k^{1.88} \quad [26]$$

where

D_v = diffusivity (cm^2/s)

T_k = temperature ($^{\circ}\text{K}$)

by best match of graphed data.

Ranz (19) also made experimental measurements of interior temperature of falling droplets and found them to be approximately uniform throughout and equal to the wet bulb temperature of the surrounding air.

The external forces acting on the droplet were as follows:

Gravity and buoyancy:

$$W = g(\rho_l - \rho_a) \frac{D^3}{6} \quad [27]$$

where

W = gravitational and buoyant forces (N)

g = acceleration due to gravity (m/s^2)

Drag force (according to King (21))

$$D_f = \frac{C_d \rho_a A V_r^2}{2} \quad [28]$$

where

D_f = drag force (N)

C_d = drag coefficient (dimensionless)

$A = \frac{\pi D^2}{4}$ = projected area of the particle (m^2)

V_r = velocity of the particle relative to air (m/s)

and

$$C_d = \frac{24}{\text{Re}} \quad | \quad \text{Re} < 1$$

$$C_d = f(\text{Re}) \quad | \quad \text{Re} > 1$$

where $f(R_e)$ is Eisner's classic empirical relationship (see Figure 12).

Particle dynamics involved were as follows: Smith (22) used analysis of momentum changes in an evaporating, falling spray droplet to develop the equation

$$m \frac{dv}{dt} = F - V_e \frac{dm}{dt} \quad [29]$$

Where

m = mass (kg)

F = an external force acting on the droplet (N)

V_e = velocity of the ejected (evaporated) mass relative to the droplet, i.e. $V_e = -V_e$

Therefore the movement of the particle due to evaporation is as though subject to an outside force of $(V_e \frac{dm}{dt})$. Obviously, if V_e is opposite in direction to V , this apparent force tends to increase V . The dynamics of the particle, then are as drawn in Figure 13.

The actual force D shown is

$$D = D_f + V_e \frac{dm}{dt} \quad [30]$$

the sign being negative rather than positive since $(\frac{dm}{dt})$ is negative, i.e. the droplet is losing mass.

X and Y components of force F are

$$F_x = D \sin \phi \quad [31]$$

$$F_y = W - D \cos \phi \quad [32]$$

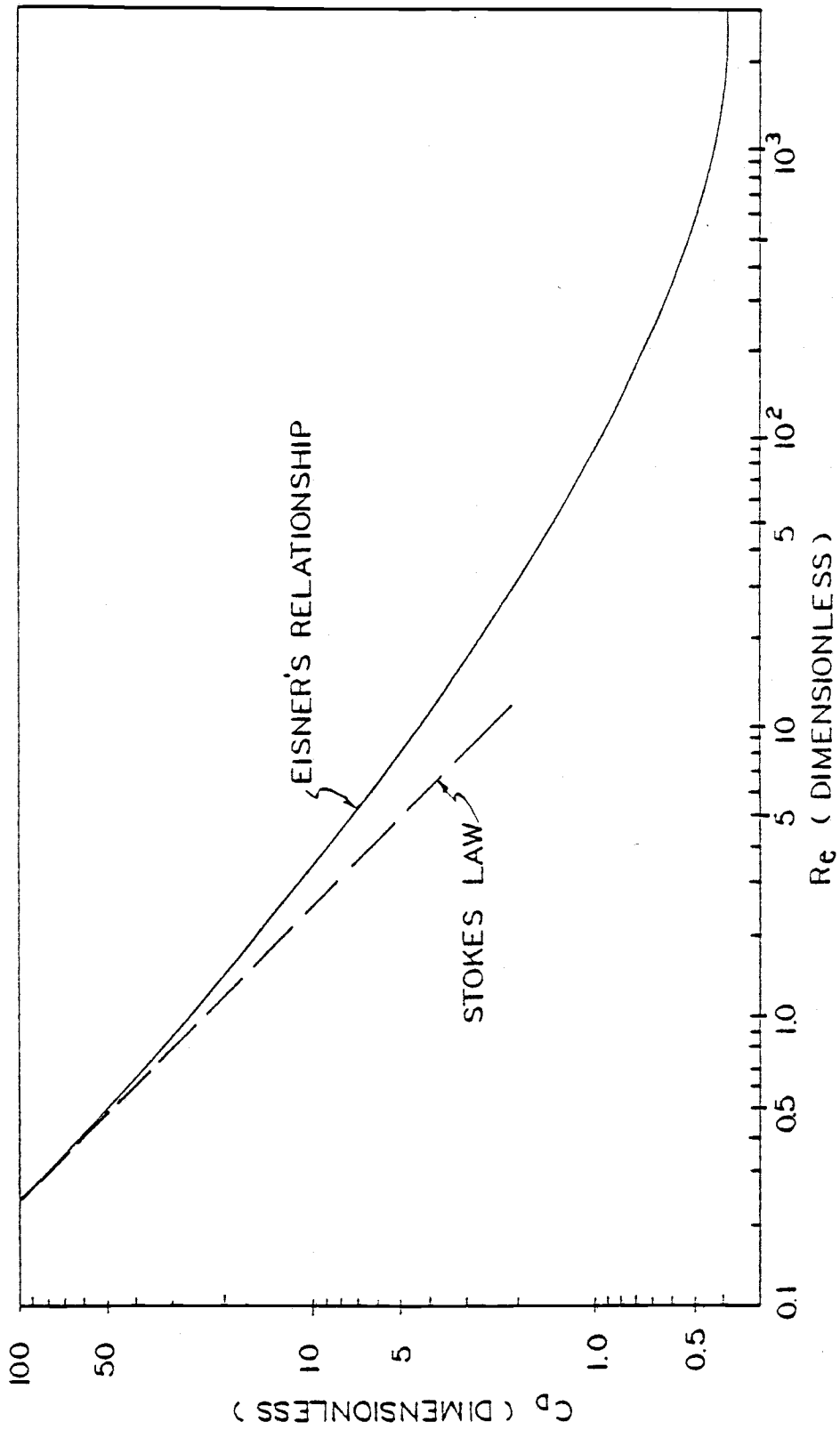


Figure 12. Drag coefficient for a sphere (from Ref. 39).

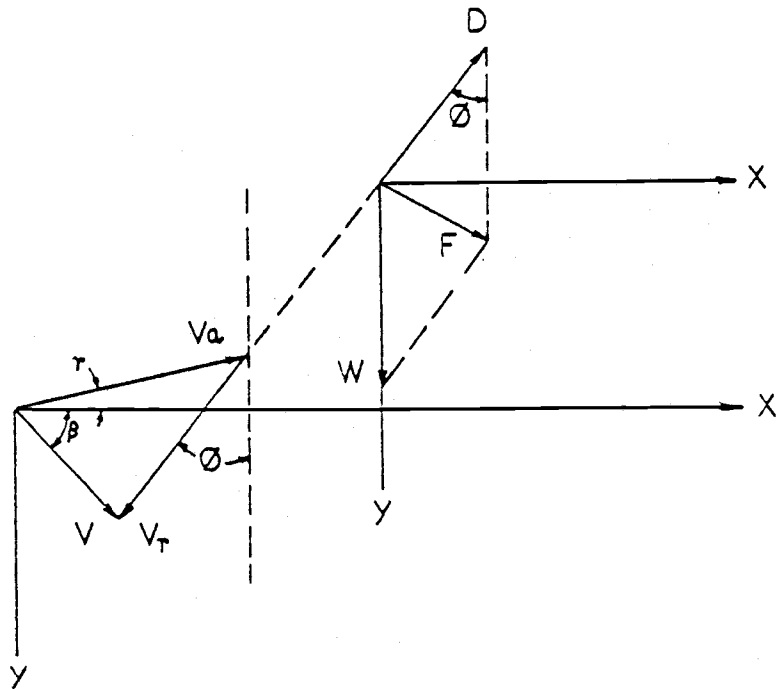


Figure 13. Diagram of particle dynamics (from Ref. 16).

Where X and Y = references axes

τ = angle of wind relative to x axis

β = angle of droplet travel relative to x axis

V_a = wind velocity

V = droplet velocity

V_r = droplet velocity relative to air

W = weight and buoyancy

D = drag and evaporative forces

F = combined forces acting on droplet

Droplet acceleration is thus

$$\ddot{x} = \frac{d^2(x)}{dt^2} = \frac{D \sin \phi}{m} \quad [33]$$

$$\ddot{y} = \frac{d^2(y)}{dt^2} = \frac{W - D \cos \phi}{m} \quad [34]$$

Integration with time yields \dot{x} and \dot{y} components of velocity; and velocity

$$V = (\dot{x}^2 + \dot{y}^2)^{0.5} \quad [35]$$

$$\beta = \frac{\pi}{2} - \arcsin (\dot{x}/V) \quad [36]$$

Hence, once the velocity V is known, velocity relative to air is

$$V_r = (V_a \cos \gamma - V \cos \beta)^2 + (V_a \sin \gamma + V \sin \beta)^2 \quad [37]$$

and
$$\phi = \arcsin \left(\frac{V_a \cos \gamma - V \cos \beta}{V_r} \right) \quad [38]$$

In the model, Eshbach's dynamic viscosity-temperature equation was used.

$$\mu = (1 \times 10^{-7}) e^{(1.258 + 0.0012627T)} \quad [39]$$

Where

$$\mu = \text{dynamic viscosity (lb-sec/ft}^2\text{)}$$

$$T = \text{temperature (}^\circ\text{F)}$$

These equations were used by Goering, Bode and Gebhart (16) to develop the computer model for a falling, evaporating droplet. The model breaks the fall into very short time periods, estimating the changes during each. The program stops when the drop reaches the ground.

Derivation of Equations Predicting
Ammonia Loss in the Model

In order to determine the rate at which ammonia is lost from the droplet, it is necessary to return to the original equations by Lewis and Whitman (17) (Eq. [14], [15]) for the two-film, two resistance theory. Since the two resistances are additive, when one is found to be orders of magnitude smaller than the other, it can be assumed to be negligible in comparison. According to Welty, Wicks and Wilson (13), the relative magnitudes of individual phase resistances depends on the solubility of the gas. For a system involving a soluble gas, such as ammonia in water, we may conclude that the gas phase resistance is essentially equal to the overall resistance. In systems involving gases of low solubility, such as carbon dioxide in water. the gas phase resistance may be neglected, and the overall coefficient is essentially equal to the individual liquid phase coefficient. Therefore, in this case, the molar flux rate can be expressed by

$$N_A = k_c (C_{A,s} - C_{A,\infty}) \quad [40]$$

Where

$C_{A,s}$ = concentration of component A at droplet surface

$C_{A,\infty}$ = concentration of component A in bulk air

Assuming the concentration of ammonia in the bulk air to be negligible,

$$N_A = k_c C_{A,s} \quad [41]$$

In order to evaluate k_c , Frössling's equation was used, so that

$$k_c = \frac{D_{AB}}{D_p} [2.0 + 0.6 Re^{1/2} Sc^{1/3}] \quad [42]$$

In Welty, Wicks and Wilson's (13) tables, they list the value of D_{AB} for ammonia/air systems as equal to 0.198 cm/sec at 273°K and 1 atm pressure.

Hirschfelder, Bird and Spotz (23) attempted to account for intermolecular forces in order to evaluate the diffusion coefficient for gas pairs of non-reacting molecules, and developed the equation:

$$D_{AB} = \frac{0.001858 T^{3/2} \left(\frac{1}{M_A} + \frac{1}{M_B}\right)^{1/2}}{P \nabla_{AB}^2 \Omega_D} \quad [43]$$

Where

T = temperature (°K)

P = pressure (atm)

M_A = molecular weight of species A (g/mol)

M_B = molecular weight of species B (g/mol)

Ω_D = the "collision integral"

∇_{AB} = the "collision diameter" for species A and B

Therefore, to correct diffusivity to existing temperatures and pressures,

$$\frac{D_{AB2}}{D_{AB1}} = \frac{T_2^{3/2} P_1 \Omega_D @ T_1}{T_1^{3/2} P_2 \Omega_D @ T_2} \quad [44]$$

Evaluating the quantity $\frac{\Omega D @ T_1}{\Omega D @ T_2}$ at the most extreme temperatures feasible changed the value of D_{AB} by less than 5 percent, and was therefore considered equal to unity, so that

$$D_{AB2} = D_{AB1} \frac{P_1}{P_2} \left(\frac{T_2}{T_1} \right)^{3/2} \quad [45]$$

or, using the known values of P_1 , T_1 and D_{AB1} as listed in Welty, Wicks and Wilson's (13) table,

$$D_{AB2} = \frac{4.39 \times 10^{-9} T^{3/2}}{P_2} \text{ in m}^2/\text{s} \quad [46]$$

The dimensionless Schmidt number is

$$Sc = \frac{\mu}{\rho D_{AB}} \quad [47]$$

but since

$$\rho = \frac{P}{RT} \quad [48]$$

where

P = pressure (Pa)

R = gas constant $\frac{\text{Pa} \cdot \text{m}^3}{\text{kg} \cdot ^\circ\text{K}}$

T = temperature (K)

combination of equations [46], [47] and [48] and plugging in the value of R as $8.314 \frac{\text{N} \cdot \text{M}}{\text{mole} \cdot ^\circ\text{K}}$

$$Sc = \frac{\mu}{5.28 \times 10^{-10} T^{1/2}} \quad [49]$$

In order to evaluate the concentration of ammonia at the surface of the droplet, $C_{A,s}$, from the concentration in the bulk droplet, $C_{A,l}$, the dimensionless constant K_D was used such that

$$K_D = \frac{C_{A,s}}{C_{A,l}} \quad [50]$$

Note that the value of K_D will be equal to the Henry's Law constant multiplied by $(\frac{1}{RT})$. Since the Henry's Law constant also varies with temperature, no linearity is lost by this combination.

Using tables from Stephens' (24) collection, K_D was found to vary with concentration at extremely high concentrations (levels at which ammonia molecules interact), but at reasonably low concentrations, became single valued at constant temperature. The values for varying temperatures were matched within the variation of the experimenters by the formula:

$$K_D = 2.31 \times 10^{-5}T - 6.12 \times 10^{-3} \quad [51]$$

Where T is in $^{\circ}K$

By definition,

$$C_{A,s} = K_D C_{A,l} \quad [52]$$

Since surface area,

$$A_s = \pi D_p^2 \quad [53]$$

multiplying Equation [41] by the surface area,

$$W_A = \pi D_p^2 k_c C_{A,s} \quad [54]$$

Where

$$W_A = \text{mass rate of flow (kg/s)}$$

Note that this equation is identical to Ranz and Marshall's (19)

(Eq. [17]) where W_A equals $\frac{dm}{dt}$ with a conversion factor for units.

To find the mass lost within any segment of time,

$$n_{1,i} = W_A (\Delta t_i) \quad [55]$$

Where

$$n_{1,i} = \text{mass lost in time segment } i \text{ (kg)}$$

and

$$n_{1,\text{total}} = \sum_0^I n_{1,i} \quad [56]$$

The above equations were added on to Goering, Bode, and Gebhart's (16) program, using the same time increments (Δt) as those in the program. At each t , the variables Re , D_p , $C_{A,L}$, and all values dependent on those variables were recalculated.

Not all of the ammonia analyzed as present is actually available or removal during sprinkling. Since ammonia is in equilibrium with ammonia ion in the form



only the ammonia in the non-ionized form can actually be volatilized during spraying. Using the Henderson-Hasselblack equation

$$\text{pH} = \text{pKa} + \log \frac{s}{a} \quad [57]$$

Where

pKa = negative log of dissociation constant

s = concentration of salt form (NH_3)

a = concentration of acid form (NH_4^+)

Using total analyzed ammonia nitrogen as equal to unity. or

$$s + a = 1 \quad [58]$$

$$a = 1 - s \quad [59]$$

Plugging this back into equation [57] and solving for s yields

$$s = \frac{1}{[\log^{-1}(\text{pKa} - \text{pH})] + 1} \quad [60]$$

It was assumed that pH does not change significantly over the period that the droplet is in the air and that the ammonia ammonium ion equilibrium is reached in a period less than the time increments of the program (more than 10^{-3} seconds).

Therefore, the actual amount of ammonia able to be lost was calculated for each iteration as equal to the predicted loss assuming all can be volatilized, times a factor equal to the amount called "s" in equation [60].

THE MODEL: ITS USE AND LIMITATIONS

The model is directly based on Equations [14] through [60]. Goering, Bode, and Gebhart's model, based on Equations [14] through [39] predicts the droplet's trajectory and evaporation, while Equations [40] through [60] predict ammonia losses. There are thirteen independent input variables: ambient air temperature, relative humidity, atmospheric pressure, horizontal and vertical components of wind speed, initial spray velocity, horizontal and vertical components of spray direction, nozzle height, nozzle pressure, droplet diameter, ammonia concentration and pH. Based on these, all dependent quantities are determined within the program, for example, droplet surface area and rate of mass transfer. Certain quantities are considered constant for a water/ammonia/air system, such as density of the droplet, and mean molecular weight of the air.

The model determines initial conditions just prior to ejection, then sends the droplet a short distance (just under a half an inch), based on those conditions. Here the program stops, prints time, x, y, and z components of velocity, x, y, and z components of distance, droplet diameter, Reynold's number, quantity of ammonia lost, and percent of ammonia left. Next, changing factors are taken into account, those above plus ones dependent on them, such as drag force and ammonia concentration. It then calculates the new initial conditions, travels another short distance, and repeats the process until the ground is reached (see Figure 14).

The units for the program are varied: Goering, Bode and Gebhart used English units for ease of use. Although some calculations are then performed in the original units. they change most to the metric,

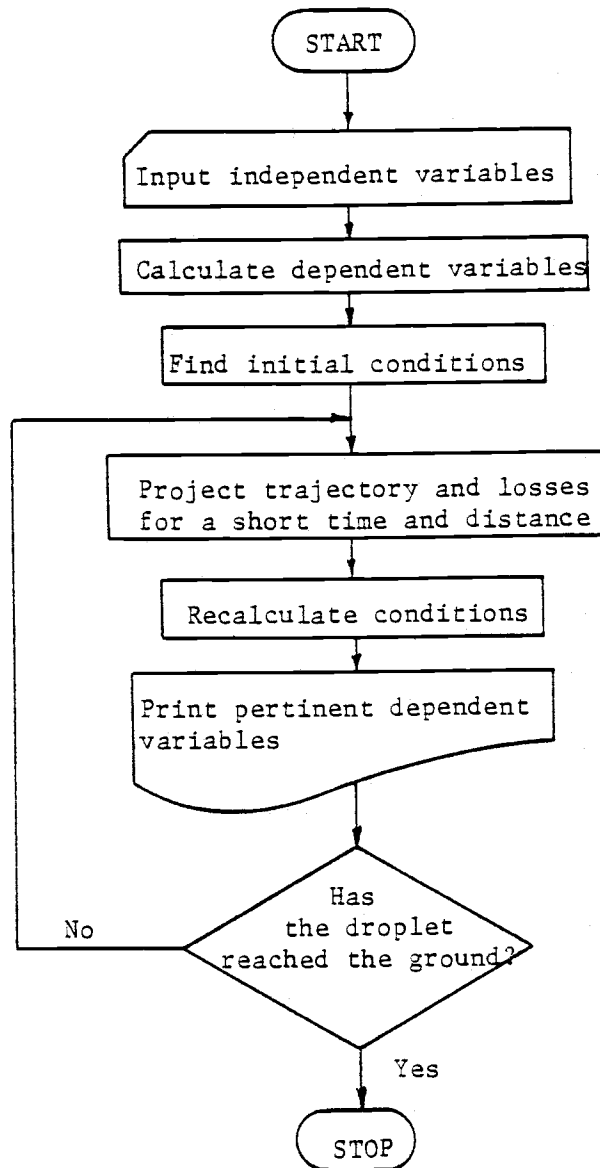


Figure 14 General flowchart of the programmed model.

c.g.s. system. For the purposes of this thesis, more recent engineering articles and books were used which, in spite of variation in units, usually included the metric equivalent in S.I. units; therefore, S.I. units were used. All values were reconverted to English units for the output, with the exception of ammonia lost, which remains in gram mols, since it was assumed that the average user would be more interested in the percentage left.

As the program is presently designed, use is extremely simple.

The program requests input variables in specific units:

```

ENTER TEMPERATURE (DEG F)
ENTER RELATIVE HUMIDITY (%)
ENTER ATMOSPHERIC PRESSURE (PSI)
ENTER WIND SPEED COMPONENTS (MPH)
    WXY-MPH
    WZ-MPH
ENTER INITIAL SPRAY VELOCITY (MPH)
ENTER COMPONENTS OF SPRAY DIRECTION
    THETXH
    THETAZ
ENTER NOZZLE HEIGHT (INCHES)
ENTER NOZZLE PRESSURE (PSI)
ENTER MAXIMUM DROPLET DIAMETER (MM)
ENTER INITIAL NH3 CONCENTRATION (MOLS/M3)
ENTER PH
  
```

The program then reprints the input variable values to assure they are correctly recorded before proceeding with the calculations.

Oddities of the program which should be noted before use are:

- 1) Angle inputs are in degrees clockwise and are oriented about reference axes in which "Z" is vertical downward, i.e., a droplet ejected at THETXH and THETAZ of zero will be shot directly down toward the ground.
- 2) Input ammonia concentration is in g-mols/m³.
- 3) Read-back of droplet size, to check the input, changes the units

from millimeters to microns and so shows the value increased by a factor of 10^3 .

4) Use of wind requires orienting the nozzle correctly to the wind: with THETXH of zero and WXY-MPH greater than zero, wind is coming from directly behind the sprinkler head and ejected droplet. The variable WZ-MPH gives the wind a vertical component of velocity.

5) The printout lists values of time, velocity components, distance components, droplet diameter, Reynold's number, ammonia loss, and percent ammonia left for each iteration. Cumulative affects are summed so that the last line shows the total time, distance, ammonia loss and percent ammonia left and the final velocity, droplet diameter, and Reynold's number.

METHODS AND MATERIALS

In order to collect ammonia loss data during sprinkler irrigation of animal wastes, the OSU Swine Research Center waste disposal system was used as the basic source. In that system 800 swine are kept on partially slatted floors over twelve holding pits. Every three to five days the pits are emptied (gravity fed) into an anaerobic lagoon. Although no water is used for the flushing of pits, a total of several hundred gallons of water daily from spillage, a few flush gutters and from the washing of alleys empty into the pits. The lagoon measures approximately 100 ft. by 120 ft. by $7\frac{1}{2}$ ft. deep and its effluent flows into a conical pumping pit 50 ft. in diameter and 6 ft. deep. A coarse filter of hardware cloth (see Figure 18) prevents solids from clogging the pump. The pump draws effluent from the pit into a sprinkler irrigation system onto surrounding land (Figure 15).

The existing system was modified by the addition of a Manning Proportional Sampler, model S-4040, drawing 400 ml. samples from within the pump pit filter every ten minutes. Sample receivers were alternated non-acidified bottles with ones which were preacidified with a few drops of concentrated sulphuric acid to result in a final sample pH less than 3.0, allowing analysis of all nutrients considered pertinent to the study.

In addition, an extra lateral and sprinkler were tapped into the end of the existing irrigation main line. All piping was Moore-Rane "3-inch" aluminum; the sprinkler head was a Rainbird 30 TNT (24) with a $9/64$ " (0.35 cm) diameter nozzle. The sprinkler was on a riser 19"

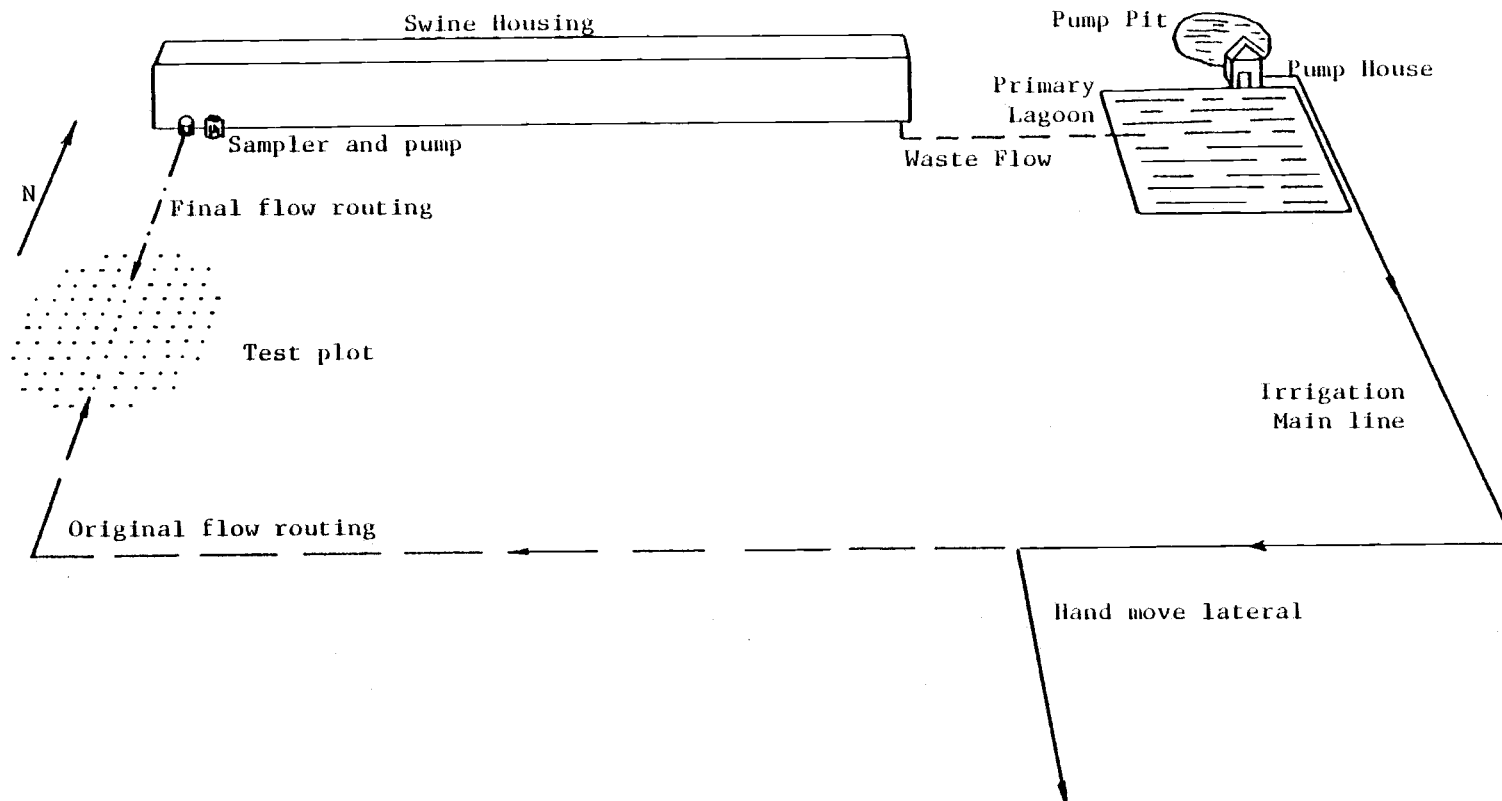


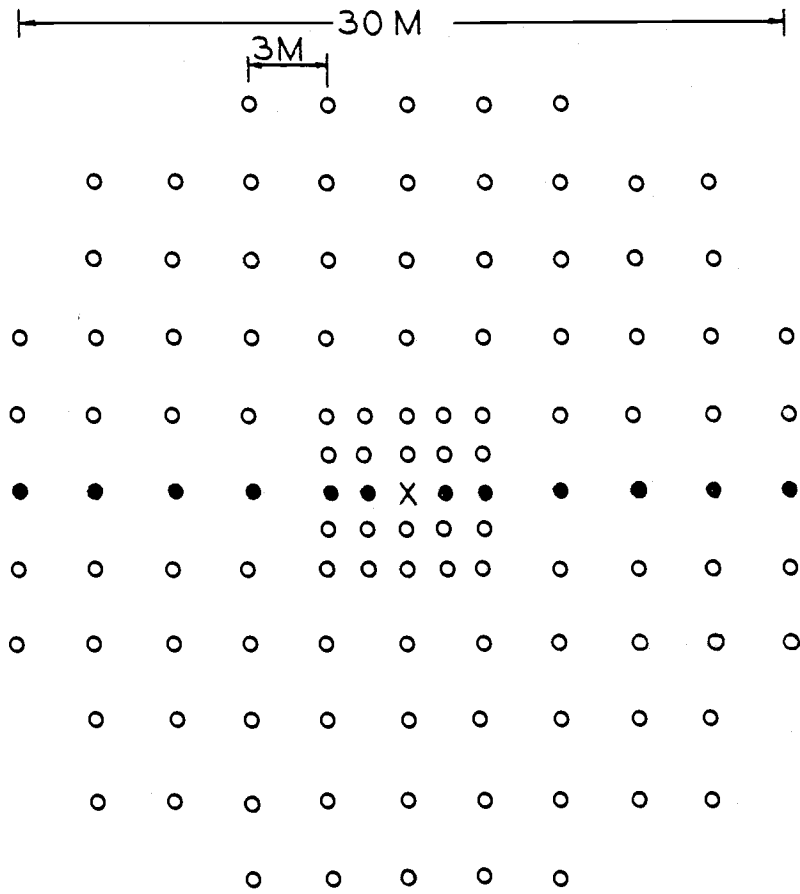
Figure 15. Schematic of swine center with waste disposal system and test plot shown.

(48.3 cm) above the collector tops and a pressure gauge was tapped into this riser. Pressure remained relatively constant at 40 psi (5.8 kPa) ± 2 psi (0.3 kPa).

The sprinkler was placed in the center of a plot gridded off into 3.0 meter squares. The plot location was chosen for flatness and accessibility. Collectors were located at all junctions for a 30.0 meter diameter circle (a total of one hundred), and within a 6.0 meter diameter circle, sixteen additional collectors were placed to form a grid with 1.5 meters separating sprinklers (see Figure 16).

Samplers were constructed of PVC "3-inch" piping and bottoms were of flat PVC sheets attached with a solvent cement. Funnels were made of polyurethane, attached to splash cups of PVC with a contact cement. The upper edges of the cups were lathed to form a sharp delineation between those drops entering and those not entering with a minimum of splash (see Figure 17). Each, with the exception of one row, was acidified with concentrated sulphuric acid prior to use so that the final sample had a pH less than 3.0.

After a week of sampling (July 15-21), the Swine Center's waste system clogged due to excess solids, and a decision was made to interrupt the system and remove solids from the lagoon. The waste source was shifted to pits beneath the swine, a small contractor's pump providing flow to the sprinkler at the same pressure head. A separate filter was built for the purpose, modelled after the one used in the lagoon (see Figure 18). When the pits became low on liquid (a situation which occurred four times in a six-week period) tap water was added and the solution allowed to equilibrate for 24 hours. Concentrations of ammonia



- ACIDIFIED COLLECTORS
- NON-ACIDIFIED COLLECTORS
- X SPRINKLER LOCATION

Figure 16. Grid of collectors.

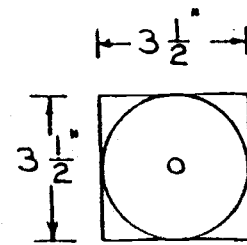
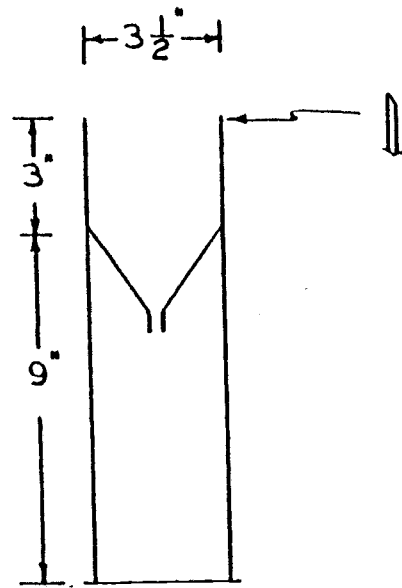


Figure 17. Collector design.

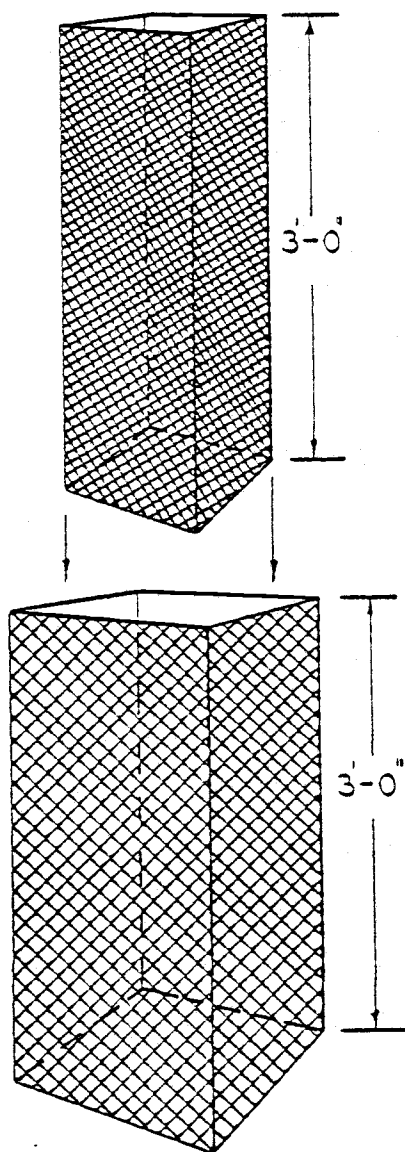
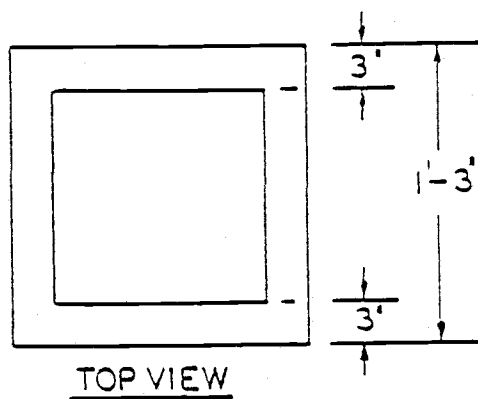


Figure 18. Filter design.

nitrogen varied between 50 mg/l and 200 mg.l, the lower value occurring after the addition of water.

When operating, the sprinkler produced two separate spray patterns, one between 3.0 and 15.0 meters from the sprinkler head and one at less than 3.0 meters. The spray at a distance ("far") was produced by the main spray upwards from the horizontal at 30°. The "near" pattern was produced by the splash of the impactor, and sprayed downward from the horizontal at an average angle of 15°.

The usual run was as follows: the sampler's bottles were acidified (alternate); the field collectors were acidified, except for a single row; the pump was started; the sampler was started; the sprinkler was allowed to drain away from the collectors for a few minutes to assure steady state conditions. During the sampling period (1½ to 2 hours), wind speed, air temperature, and relative humidity were checked twice: wind speed by an anemometer, and relative humidity by sling psychrometer. If wind speed exceeded 4 mph, or if rain fell, the run was aborted. At the end of the sampling period all systems were shut down, and five samples were carried back; each was formed by combining all samples of a given category in a single vessel, and drawing an "average" sample for that category from the vessel. The samples were classified as sampler/acidified, sampler/non-acidified, field/near (acidified), field/far (acidified), and field/non-acidified. These were analyzed within 24 hours. Spot checks of lagoon pH, droplet pH, and lagoon temperature were also made. Droplet pH was measured by catching a small quantity of spray in a beaker and immediately analyzing its pH with field electrode and meter. These results were cross-checked by analyzing pH

of non-acidified spray samples in the lab. Lagoon pH was measured both in the field and in the lab.

The non-acidified inlet sample and the non-acidified field samples were analyzed for phosphate, total dissolved solids, volatile dissolved solids, total suspended solids, and volatile suspended solids concentrations. The acidified samples: "sampler", "near", and "far", were, in addition to ammonia, analyzed for total Kjeldahl nitrogen and chemical oxygen demand concentrations. All analyses were performed according to Standard Methods for the Examination of Water and Wastewater (28).

Ammonia nitrogen analysis was performed according to the suggested method for acidometric analysis, except that extra duplicates were sometimes carried out and titrated with lower concentrations of acid to increase precision. Those samples tested for total Kjeldahl nitrogen were also analyzed by acid titration rather than colorimetrically.

Phosphate was determined colorimetrically by the vanadomolybdic acid method (28). Solids and COD analyses were carried out with no variation from the prescribed method.

Droplet size was measured by the method developed by Laws and Parsons (29) and revised by Meyer (30). Fresh, bleached, white flour was sifted into pans to a depth of 3/4" (1.9 cm), then struck off with a straight edge. Within an hour, the pans were exposed to spray. Immediately afterwards, they were dried for 24 hours at 38°C. After drying the flour pellets formed by the droplets were separated from the flour by a 50 mesh sieve. They were then weighed, and the size of the droplet calculated according to Meyer's equation:

$$R = 1.05 M_p^{0.062} \quad [61]$$

Where:

R = ratio of droplet mass to pellet size

M_p = pellet mass (mg)

The resulting mass was divided by $\frac{\rho_l \pi}{4}$ and the square root taken to calculate droplet diameter:

$D_p = 2.76$ mm for far droplets

$D_p = 1.03$ mm for near droplets

These agreed fairly closely with Kohl's (31) analysis of droplets from agricultural sprinklers by the same method. His results are more fully examined in Appendix II.

The velocity of the spray was obtained by using a pitot tube at the nozzle tip. Changing stagnation pressure (psi) to velocity gave an initial velocity for both sprays of 34.2 mph (15.3 m/s).

The pH checks all showed a pH of 7.0 ± 0.1 , initially and after spraying. Samples were taken at air temperatures varying from $50^\circ - 90^\circ\text{F}$ ($10^\circ - 32^\circ\text{C}$). Relative humidity varied from 10 percent to 90 percent, the former value usually occurring at high temperatures, the latter at low. The exception was one rainy period of about 5 days (August 20-25) when samples (#18-22) were taken and analyzed only if completed before actual precipitation occurred.

Additional analyses were carried out at the end of the testing period (September 7-15) to determine the effects of spraying on coliform count and the effect of herbage on ammonia loss after droplet impact. These methods, materials, results, and discussions are reviewed in Appendix I.

RESULTS AND DISCUSSION

Analysis of data is based on comparison of measured losses to predicted losses. Losses of ammonia during sprinkler irrigation of wastes was found by subtracting ammonia concentration in field collectors from ammonia concentration at inlet sampler, and dividing by inlet sampler's ammonia concentration to express losses as percent ammonia loss. Analysis of the computer model's prediction of variation of ammonia loss with any given factor was carried out by plugging in a set of standard conditions and varying only the factor under consideration. The one exception was the variation of temperature and humidity. Collected data showed a definite correlation between temperature and relative humidity, in this case, as shown in Table 2.

Table 2. Variation of relative humidity with temperature during study.

Temperature ($^{\circ}$ F)	Relative Humidity (%)
100	0
90	10
80	20
70	40
60	60
50	90
40	100

Therefore, for studies of individual factors affecting ammonia losses, temperature and relative humidity were varied simultaneously according to the same pattern. Variations of losses with nozzle pressure change were not investigated to any real extent. The sprinkler head dictates

the operating pressure within a fairly small range for even distribution of water.

The standard system, called "average", for computer predicted variations was one operating at 90°F, 10 percent relative humidity, atmospheric pressure of 14.7 psi, no wind, spray velocity of 34.2 mph, spray direction 30° from the horizontal, nozzle height of 19 inches, nozzle pressure of 40 psi, droplet diameter of 1 mm, ammonia concentration of 5.88 moles/m³ (100 mg/l), and pH ranging from 7 to 10, given in each case. Note that this system is similar to the actual one used in data collection, with the notable exception of spray direction and droplet size, which were measured for "near" and "far" spray in the field system. For the model, the nozzle angle was used for direction, and Kohl's (31) measurements for the "average" droplet (see Appendix II).

Figure 19 shows variation of ammonia losses predicted with changing temperature at pH 7, 8, and 9. At any given pH, the relationship is almost linear, and increasing pH increases the slope. Note the area in which the field system operated: pH of 7.

In Figure 20, line a) shows the predicted variation of ammonia loss with pH for the far spray at 90°F (32°C) and 10 percent relative humidity. Note the similarities between this curve and that of Henderson, Bianchi, and Doreen (9) (Figure 6). The low pH segment of line a) is of the same basic shape as that of Henderson, et al. (9), but has a lower slope; however, the model predicts a sigmoidal curve overall, the slope dropping at higher pH values. Use of the "average" droplet and system (differing from the "far" in droplet size only) produced line b). Here, decreasing droplet size from 2.73 mm diameter to 1 mm diameter has

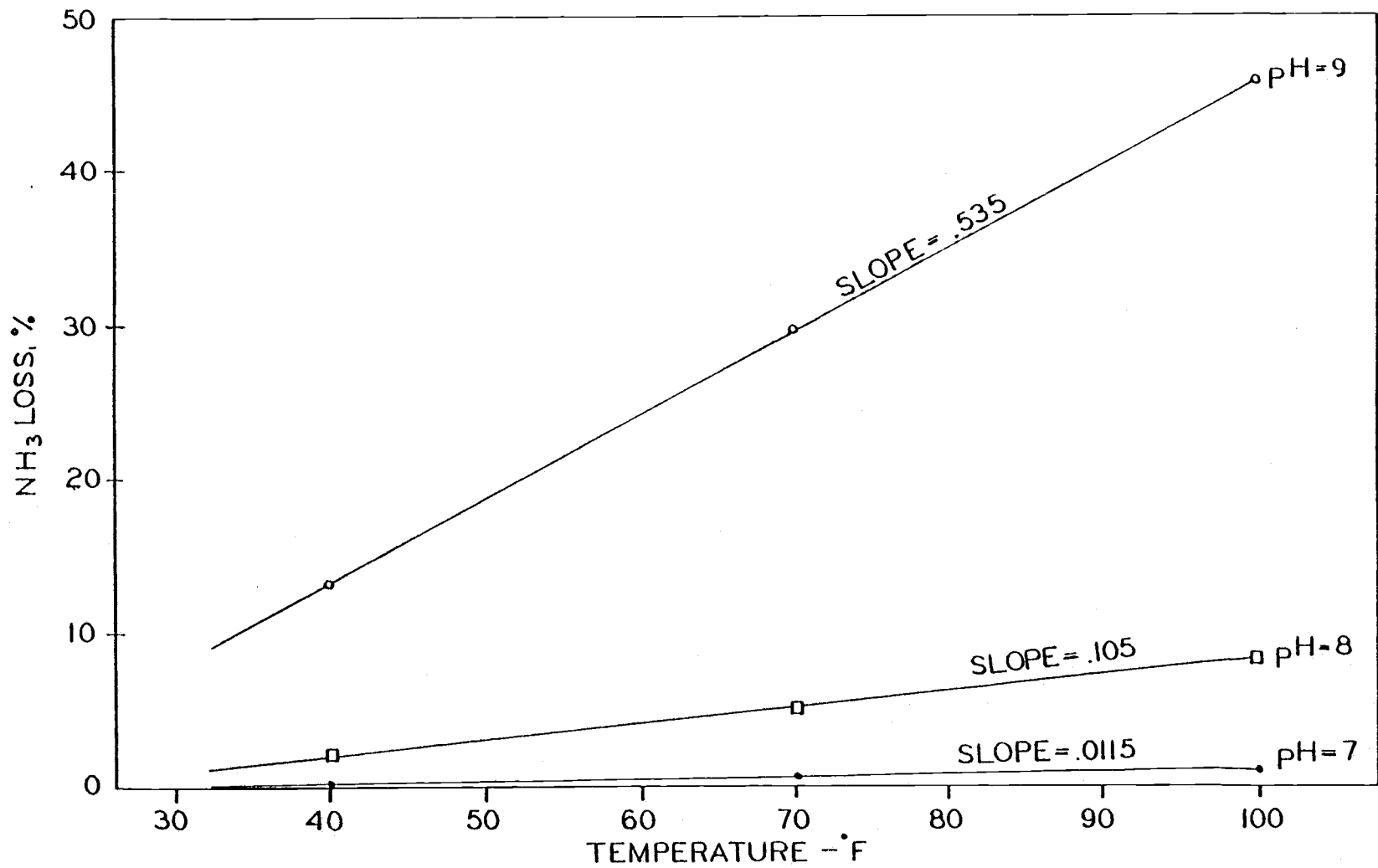


Figure 19. Predicted variation of ammonia loss with temperature and pH.

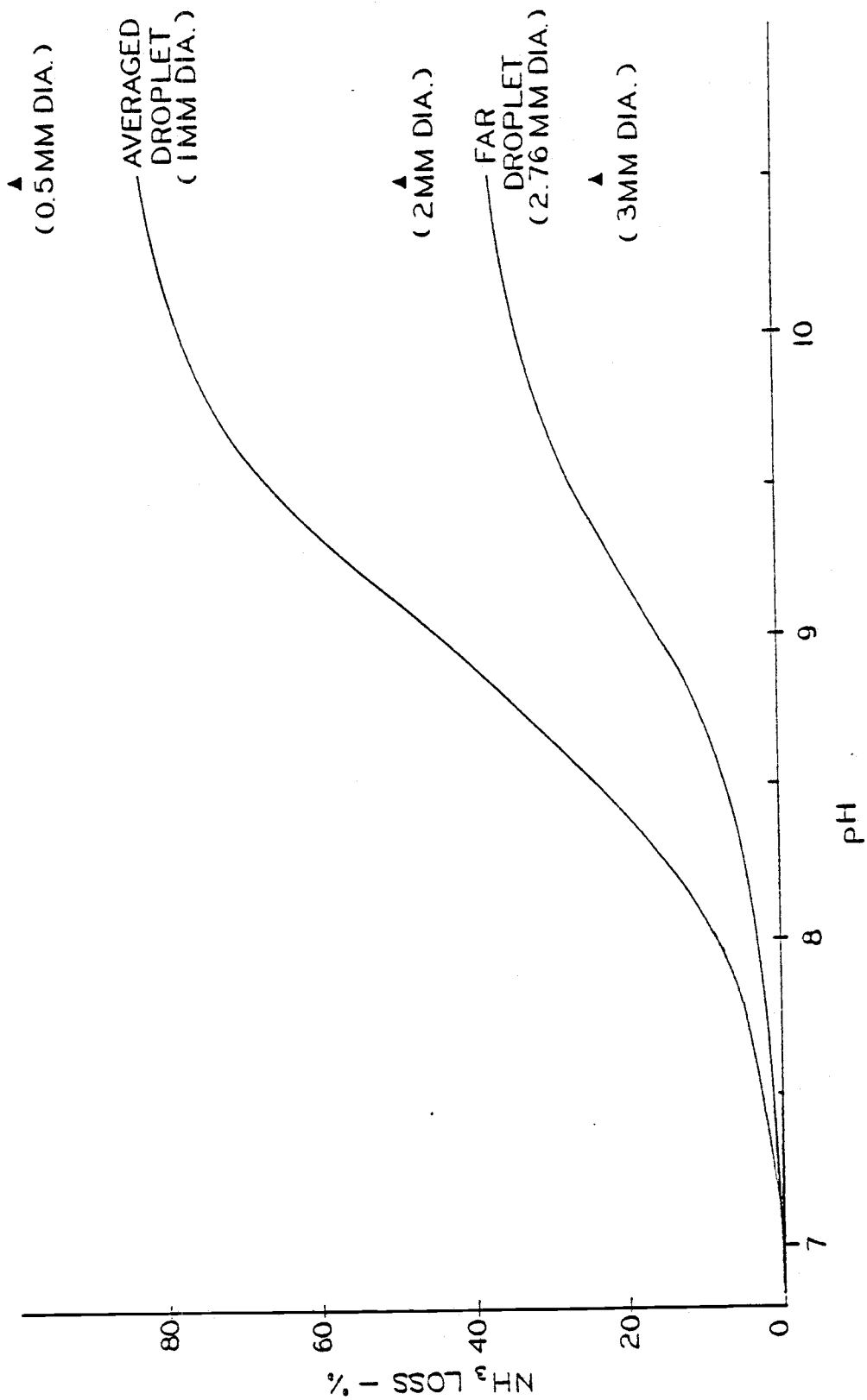


Figure 20. Predicted ammonia losses in spray: variation with pH.

more than doubled losses. As might be expected, using a droplet representative of an average system gives results much closer to those of Henderson, et al. (9), the down-curved portion still existing, but at a pH too high for practical use. At a pH of 10.5 reference points have been added to show predicted ammonia loss for droplets of diameter 0.5 mm, 2 mm, and 3 mm in the same system. It is of interest to note that a droplet diameter of 2 mm seems to represent the half-way point at extremely high pH for this system: a droplet of diameter of greater than 2 mm loses less than 50 percent of its ammonia, a droplet of diameter less than 2 mm loses more than 50 percent of its ammonia during flight.

Demonstrated in Figure 21 is the predicted relationship of ammonia loss of a droplet to the height of the nozzle at pH of 9. Even at this elevated pH, nozzle height is not the most crucial factor in ammonia loss, as an increase of 84 inches (7 feet) in nozzle height causes an ammonia loss of less than 15 percent added to the original loss of approximately 40 percent. The curve's shape is slightly convex upward, progressively taller risers producing increases in ammonia loss at a decreasing rate.

Analysis of the relationship of ammonia loss to velocity and distance travelled was performed by plots of a single droplet's flight. The droplet was an "average" one at a pH of 10.5. Figure 22 shows the predicted flight of the droplet, while Figure 23 shows the ammonia loss plotted against vertical distance. The rate of loss is almost constant with distance until near the end of the flight; even there the increased rate of loss corresponds to an increased vertical distance travelled,

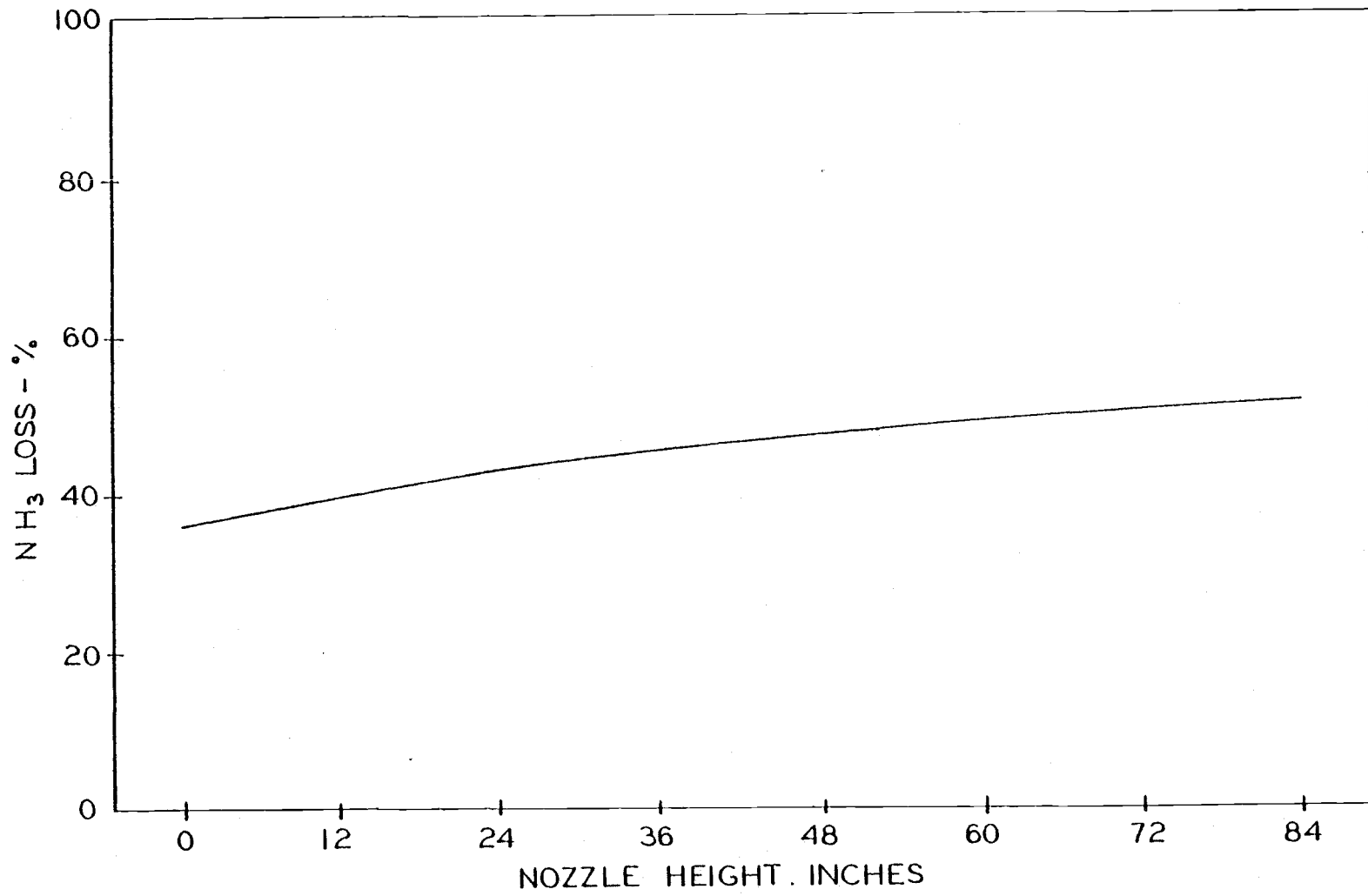


Figure 21. Predicted relationship of ammonia loss to nozzle height at pH of 9.

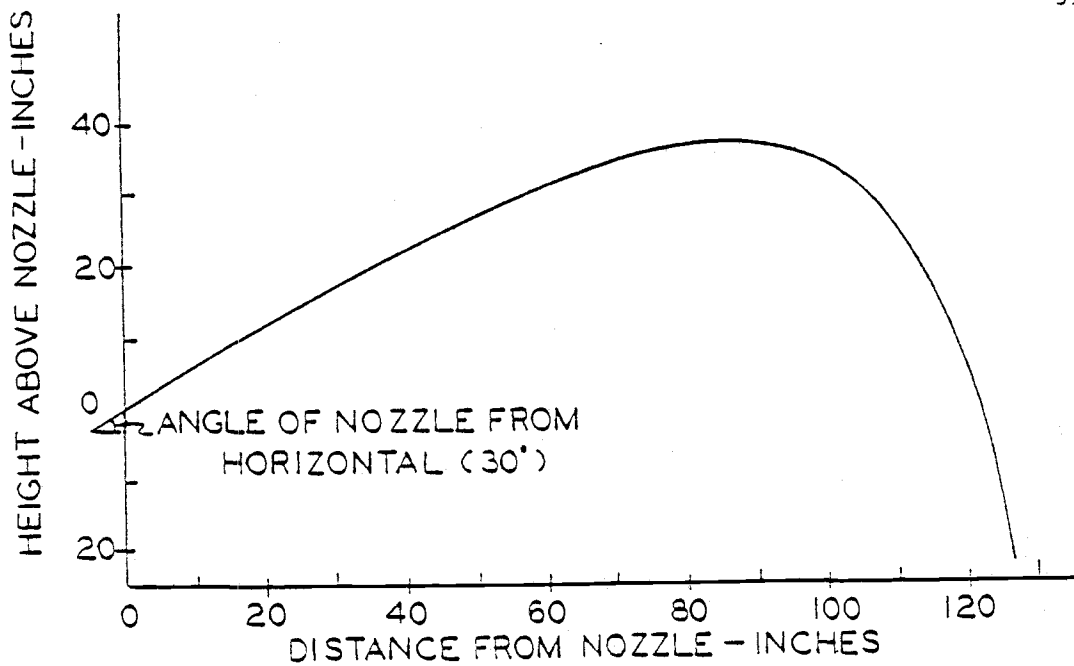


Figure 22. Droplet trajectory as predicted by computer model (average droplet)

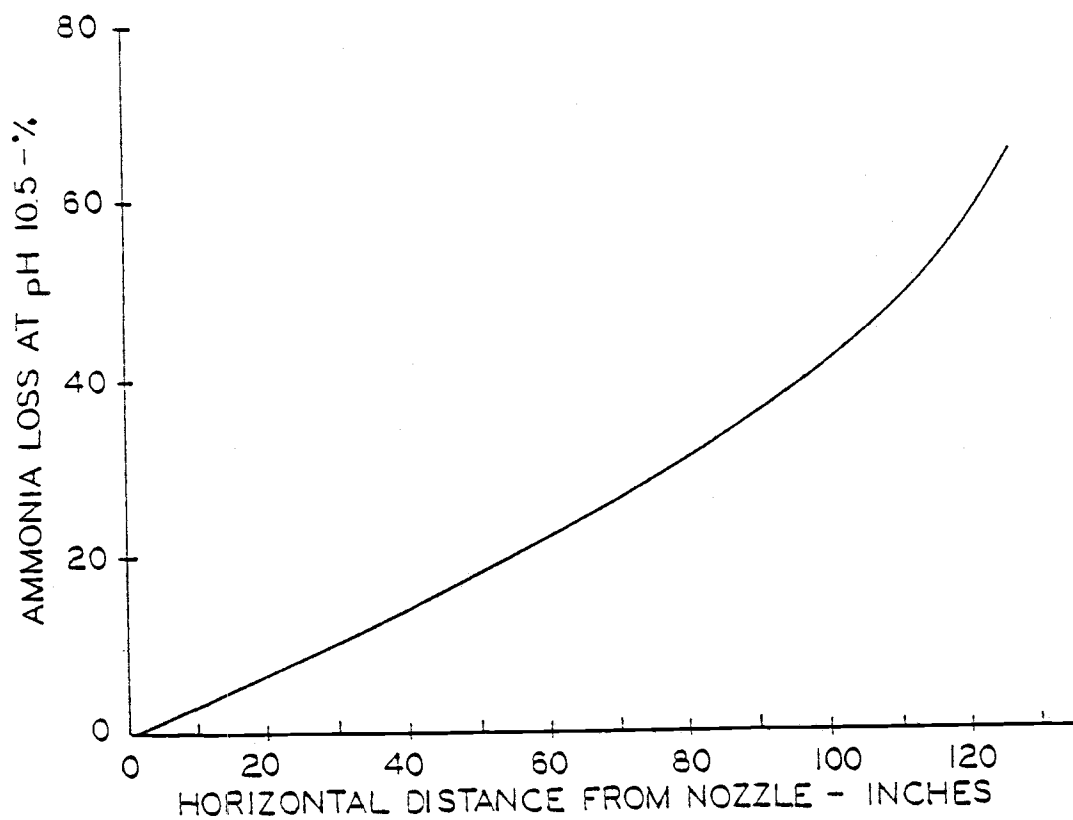


Figure 23. Predicted variation of ammonia loss with distance travelled from nozzle (average droplet).

a fact not reflected in the units of the abscissa. Figure 24 in turn shows the change of velocity with respect to distance horizontal from the sprinkler head. It is interesting to note that while the velocity undergoes a change of an order of magnitude, the rate of ammonia loss scarcely decreases at all. In general, it seems that although the distance a droplet travels is dependent on the droplet's launch velocity, the ammonia loss is more dependent on the distance travelled than on the velocity at which it is travelled.

Since the driving force for ammonia volatilization is the concentration gradient between the droplet and the air, the total ammonia loss predicted for the droplet flight is dependent on the original concentration, i.e., high concentrations of ammonia yield high losses, low concentrations yield low losses. However, losses expressed in terms of percent ammonia lost of the original amount proved to be independent of the original concentration of ammonia.

The system used for data collection functioned in a very limited segment of the model's total capacity for predictions. The pH remained relatively constant at a value of 7.0; note (Figures 19, 20) the limits this places on ammonia loss. Concentrations of ammonia averaged around 100 mg/l, and even the best suggested methods of measuring ammonia concentration at this level have an accuracy of no more than 0.5 mg/l. This accuracy was improved on by increasing the number of duplicates run and decreasing the concentration of the acid used for titration.

Figure 25 shows the model's prediction for the ammonia loss in the "near" spray as it varies with temperature. Line a) shows the computer predicted losses, line b) the best fit of all data points, and line c)

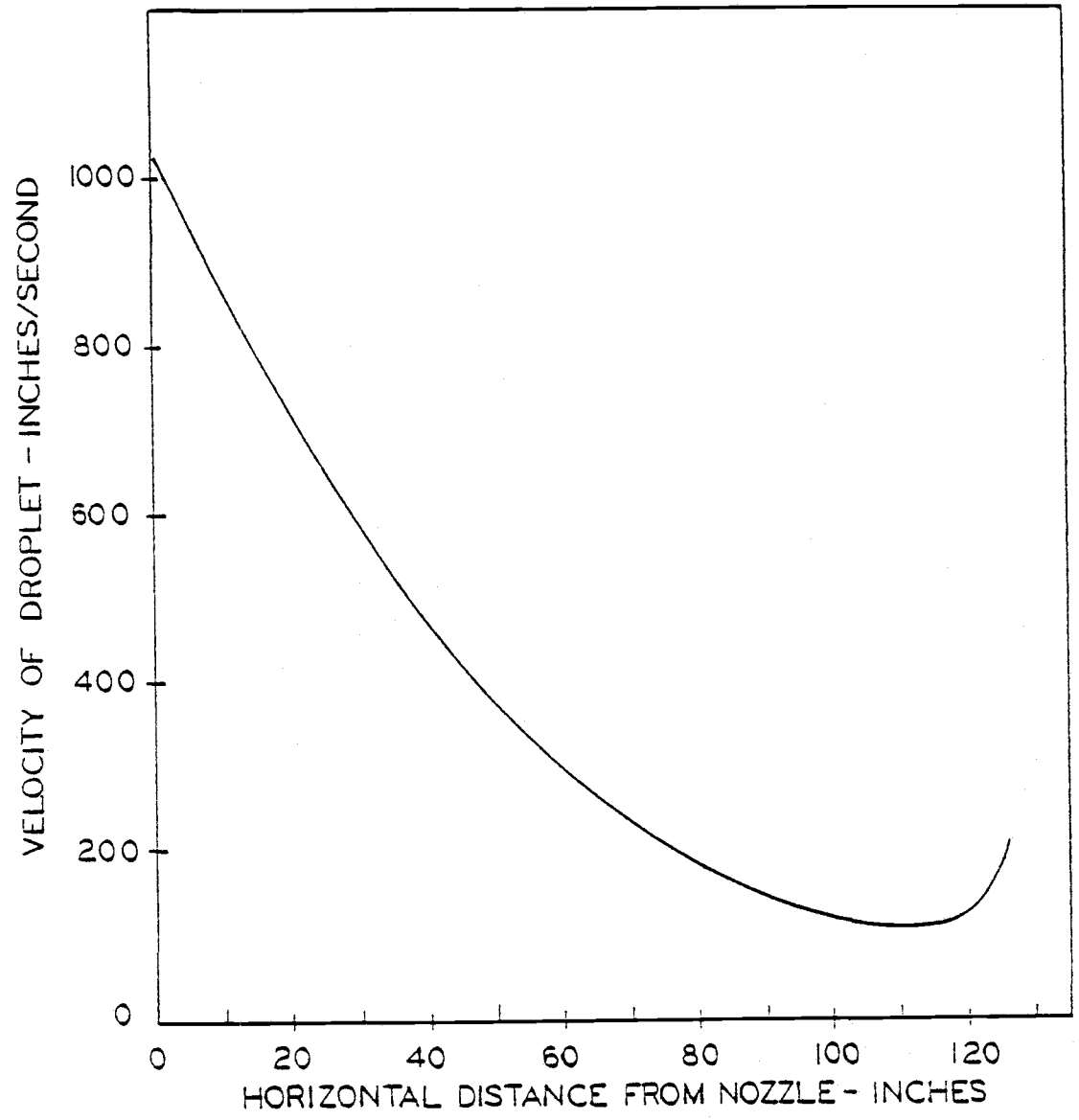


Figure 24. Predicted variation of velocity change with distance travelled from nozzle (average droplet).

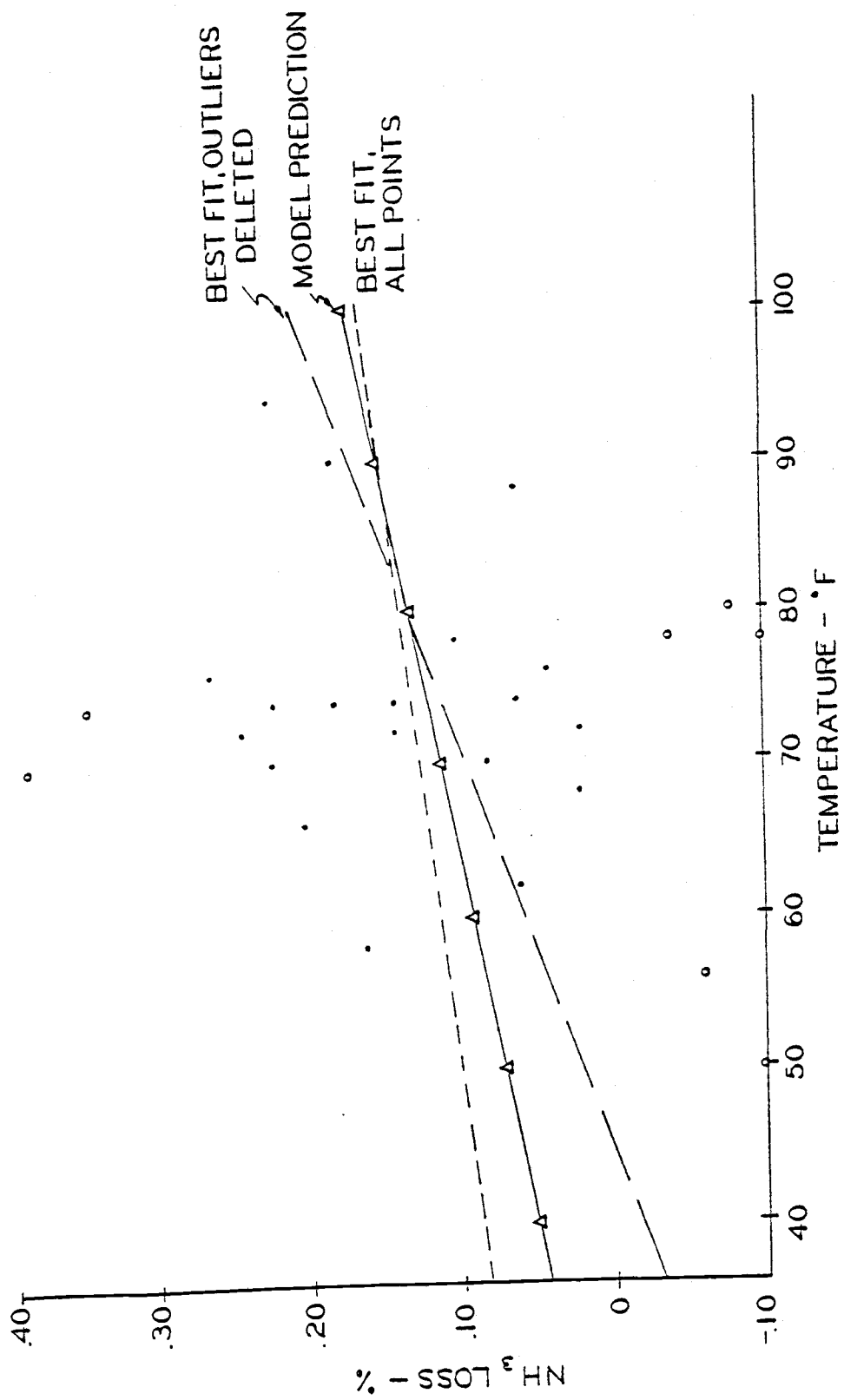


Figure 25. Ammonia loss in short-distance, small droplets ("near" spray).

the best fit of data points deleting the seven circled "outlying" points. Although the computer predicted relationship between temperature and percentage ammonia loss is not linear, it is extremely close, and statistical data analysis is based on linearity. Line b), best fit of data points was the result of least squares analysis, considering all points. In the case of line c), the seven circled outlying data points were deleted, and the least squares analysis used again. For line b), r^2 is equal to 0.0085; for line c), r^2 equals 0.0175, indicating a low correlation.

Neither line b) nor line c) varies significantly statistically from the predicted line a). Unfortunately, due to low slope and high scattering, neither are they significantly different from a line of slope zero: no change with temperature. It is questionable whether this statistical approach provides meaningful analysis of the model. Comparing Figure 25 with Figure 19, it is apparent that the data coincides with predictions within .40 percent, the limits of the analysis method. Scattering is, therefore, within the predicted range and the low slope is inherent in the model.

In Figure 26, the model predictions and data points obtained in the analysis of the "far" spray are shown. Note that the data points are far more scattered than the "near" ones. With a five-fold increase in number of collectors, and a corresponding reduction of sample volume in each, errors due to evaporation, residual moisture left in the collectors, trapped insects, and the dilution effects of the added acid would be correspondingly increased. Construction of the graph required deletion of over one-third of the data points as completely

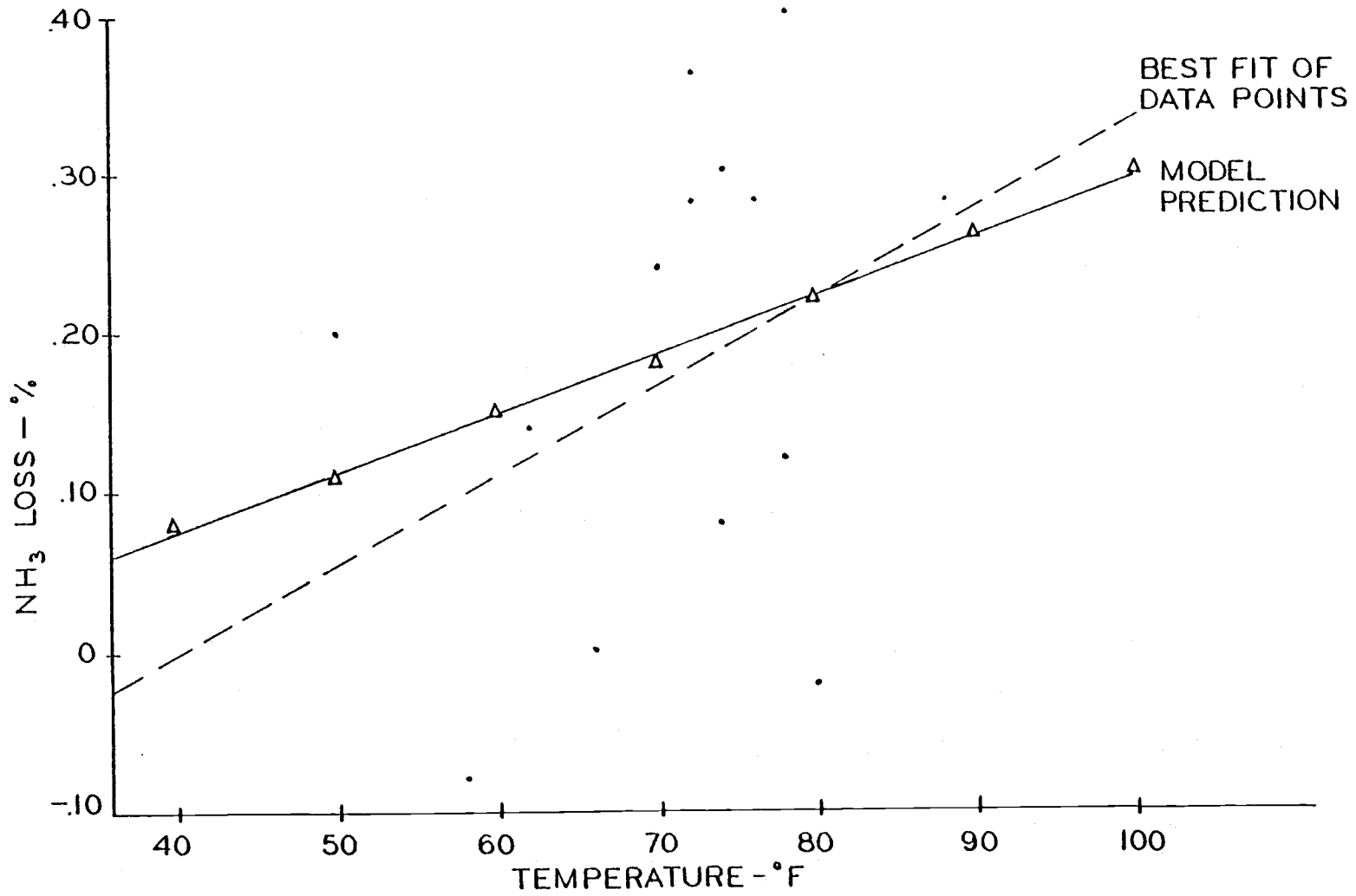


Figure 26. Ammonia loss in long-distance, large droplets ("far" spray).

meaningless, but the remainder still show an r^2 value less than 0.001, and no significant statistical difference from either the theoretical line or a horizontal one. Again, from a broader viewpoint, two-thirds of the data points matched predictions to within 0.50 percent.

Confirmation of variation of loss with pH comes from two sources: on the theoretical level, English (40) found that for ammonia loss from land applied sludges,

$$N_A = K_G P_{A,S} \quad [1]$$

and

$$P_{A,S} = \frac{(\text{TAN}_{(aq)}) \gamma_{\text{NH}_3}}{K_S \left[1 + \frac{\gamma_{\text{NH}_3} 10^{-\text{pH}}}{\gamma_{\text{NH}_4^+} K_a} \right]} \quad [2]$$

where

N_A = flux rate of ammonia ($\text{kg}/\text{m}^2\text{-hr}$)

K_G = convective mass transfer coefficient ($\text{kg}/\text{m}^2\text{-hr-atm}$)

$P_{A,S}$ = equilibrium partial pressure of ammonia at the interface (atm)

$(\text{TAN}_{(aq)})$ = total aqueous ammonical nitrogen (kg/m^3)

γ_{NH_3} = activity coefficient of ammonia (dimensionless)

K_S = solubility constant of ammonia ($\text{kg}/\text{m}^3\text{-atm}$)

$\gamma_{\text{NH}_4^+}$ = activity coefficient of ammonium ion (dimensionless)

K_a = acid dissociation constant of ammonia (dimensionless)

Combining the two formulas and assuming activity coefficients equal to unity, an assumption much truer (within 5 percent) in this dilute solution than in sludge, yields the relationship:

$$N_A \alpha = \frac{1}{\left[1 + \frac{10^{-\text{pH}}}{K_a}\right]} \quad [3]$$

This is the same as the factor by which the ammonia loss was multiplied to allow for pH in the model

$$s = \frac{1}{\left[\log^{-1}(\text{pKa}-\text{pH}) + 1\right]} \quad [4]$$

His supporting data infer that a similar approach to predicting ammonia loss variation with pH in falling droplets is valid.

Confirmation of the model's prediction of ammonia losses at high pH can also be found in the data collected by Jackson, Alban, and Wolfe (11) and by Henderson, Bianchi, and Doreen (9) (see Figures 7 and 8), who made no attempt to model losses, but whose data points agree closely with the proposed model.

Separate analyses were performed on the potential pollutants listed in Table 3. These analyses were performed according to suggested procedures with no special efforts being made to increase the precision or accuracy above the inherent abilities of the particular method. As a result, the values show more scatter, and in none was there a significant reduction in concentration during spraying.

Table 3. Average percent change in waste parameters during sprinkling.

Parameter	Average Value	Average % Loss	Standard Deviation of % loss
TKN	124 mg/l	+1.23	3.01
COD	603 mg/l	-0.32	4.13
PO ₄ -P	61 mg/l	+0.02	1.61
TDS	398 mg/l	-1.01	5.32
VDS	152 mg/l	-0.17	2.15
TSS	123 mg/l	+0.26	13.40
VSS	110 mg/l	+0.32	17.30

The experimental set-up was designed to test conditions as they actually existed. In this case, those conditions included a relatively low pH and therefore almost negligible ammonia losses. In most animal waste management systems the pH will not rise much above the 7-8 range, and the ammonia losses should, therefore, not exceed 5 percent due to absence of un-ionized ammonia. If the pH is higher, droplets smaller, their velocity greater than usual, or should wind exist, the ammonia loss could dramatically increase. The program has the capability of modeling such conditions.

There are particular weaknesses in the program. The effects of wind drift on ammonia and water loss in actual field situations is still unknown. For the purposes of this program, it was assumed that wind drift droplets behave as larger ones, so that any droplets moving for greater distances still reach the ground. If such is not the case, the program must be revised. To avoid this conflict, data from tests conducted at wind speeds above 4 mph were discounted.

The program also assumes that the spray is ejected as spherical

droplets. In fact, for the standard agricultural sprinkler the spray emerges as a stream which, as it travels, is broken up into droplets by the turbulence of its flight; these droplets quickly become spherical. Likewise, the program assumes that an "average droplet" describes the whole spray. Whether or not the simplified model can adequately predict what the actual losses will be can only be determined by further testing.

One major fallacy existed in the method of testing the theory. It was decided at the outset that data should be collected in the field, so the model would describe existing conditions. Although the program was designed to describe ammonia losses in agricultural spraying of animal wastes, it would have been more informative to have first laboratory tested the program. This would have allowed greater manipulation of the variables (pH and temperature especially) and could have been used to increase the slope and decrease the relative scatter of data points. Thus, the model should be tested under more extreme conditions to assure its adequate performance under those conditions.

CONCLUSIONS

The nitrogen content of animal wastes is of sufficient economic value as a fertilizer and sufficient hazard as a potential pollutant to warrant close analysis of losses during field application. Although some investigation of ammonia losses has been carried out for treatment systems up to the point of actual sprinkling, few studies exist for ammonia losses during sprinkling. Those few, beyond establishing that some volatilization does occur, do little to consider factors affecting the amount lost and methods of predicting those losses.

Factors affecting the rate of ammonia loss are ambient air temperature, relative humidity, wind speed, nozzle height, nozzle pressure, droplet size, spray velocity, ammonia concentration, and solution pH. The effects of these factors can be predicted in equation form for a single droplet, and, by using a computer to perform the calculations for a series of very small time increments, a prediction of ammonia losses during the flight of the droplet can be made. These predictions can be expanded to an entire sprinkler system using an "average droplet" for that system.

The pH will be low (7 to 8) in most animal waste management systems and losses will not exceed 8 percent. At higher pH values, ammonia loss will increase in a sigmoidal curve, rising rapidly, then leveling off at a pH of 10.5 to a total loss of 30 to 60 percent, depending on other factors. Droplet diameter, when halved, triples losses at pH 8 and almost doubles them at pH 10. Doubling spray velocity can increase losses by one third. Most factors (pressure, nozzle diameter) affecting

droplet size also affect velocity. The losses due to wind are similar to those due to velocity change for a single droplet, since wind speed is added to droplet velocity to give droplet velocity relative to air. However, there is no assurance that this loss can be expanded to the entire system, due to uncertainty about the fate of "wind drift". Increases in temperature cause almost linear increases in ammonia loss, a change of 10°F causing an increase in ammonia losses of about 1 percent at pH 8.

The model developed predicted ammonia losses consistent with field data collected for swine lagoon effluent. Comparison of model predictions to data collected in previous studies of sprayed fertilizers showed close agreement of the ammonia loss variation with pH.

The model should be applicable to situations in which a dilute ammonia solution is being ejected in droplets through the air. The basic premises for the analysis and model are well established ones, and therefore, the model should accurately predict the ammonia loss, assuming the idealized situation is representative of the actual one.

RECOMMENDATIONS

Collected data, although far from conclusive, shows losses within expected ranges of the predicted values, but did not prove the model's accuracy in a variety of conditions. The model should first be laboratory tested on single droplets at an elevated pH, using a variety of values for input variables. Since the model is centered around a single droplet, it lends itself well to this method of experimentation. Field testing should be carried out at a greater variety of pH's, temperatures, and humidities. If possible, testing should include analysis of ammonia losses from spraying of liquid, ammonia fertilizers, which are typically higher pH solutions.

There were several theories in the literature as to the fate of wind drift: 1) it is a complete loss, either not landing within the field or, if it lands in the field, yielding nothing of significance to the soil; 2) it retains more water and ammonia per volume than standard droplets; and 3) it behaves like standard droplets other than travelling further. The program assumes that the last is true. The validity of any prediction of sprinkler irrigation losses when wind is present will be uncertain without more research in this area.

Assumptions about the temperature of a falling droplet are that: 1) it remains at the original lagoon temperature and 2) it immediately reaches ambient wet bulb temperature. Although the latter is far more widely accepted, there is much old data supporting the former to at least some extent. More field testing is needed to lend a stronger data base to one theory or the other.

Although many researchers mentioned that losses after droplet impact were likely to far exceed losses during sprinkling, research in this area is almost non-existent. Similarly, research on the effect that various types of irrigated crops have on spray losses is extremely limited. Research in this area in particular could be of great practical value.

Certain assumptions that were made for the program held true for relatively dilute solutions stored open to the air, but would not be true for solutions of higher ionic strength or solutions stored under pressure. In particular, the program assumes that activity coefficients are equal to unity, a valid assumption for this case, but one which would cause significant errors for sludges, saline sea water, or any solution of high ionic strength. The model also assumes that pH will not change during the droplet's flight; the validity of this assumption has not been tested for all solutions. Notably, anaerobic digestion under pressure builds up large concentrations of carbon dioxide, and when these solutions are distributed on crops, pH rises rapidly as carbon dioxide is lost to the atmosphere. Whether or not this occurs significantly during the period of the droplet's flight, and the possible affect on ammonia loss is unknown. Application of the program to such situations will doubtless require modification of the model.

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APPENDICES

APPENDIX I

Secondary Experimentation

A. Coliform Counts

Five sample series were analyzed for total coliform before and after travel through the irrigation system. After irrigation and continuous sampling for a period of 1½ hours, samples were transported to the laboratory for immediate analysis. The method of analysis was the membrane filter (MF) technique using Millipore equipment and suggested methods (29). Results were as follows:

Average count (prior to spraying)	8.9 x 10 ⁶ per 100 ml
Average loss during spraying	8.8%
Standard deviation	8.5%

Although the data seem to indicate a slight reduction in coliform count during irrigation, the comparatively small change, combined with the limited accuracy of the method, render the difference insignificant. More sample runs and more duplicates might detect a reduction, but such an effort would be of questionable value since 1) there is nothing in the literature to indicate losses in coliform should occur during sprinkling (30, 31) and 2) at these levels, a 10 percent reduction in coliform has no practical significance.

Appendix III-B shows actual data collected during this study.

B. Effect of Herbage on Ammonia Losses

An approximation of ammonia losses from the time the spray strikes the grass, until it reaches the ground was made according to the following method. Using the same samplers, the funnel was filled to a height of two inches with shredded cellophane in the form known as "Easter grass". Immediately adjacent to each packed sampler was placed a standard sampler. Both were acidified with a few drops of acid in the bottom. After 1½ hours of collecting, the samples were analyzed as usual for ammonia.

Results showed a notable difference between samples with grass and samples without, although not enough samples were collected for statistical significance. Samplers with grass showed an average loss of 10.7% $\text{NH}_3\text{-N}$ as compared to those without grass with a standard deviation of 3.2%. Appendix III-C lists collected data.

There was a tendency for the "grass" to pack down enough to cause the liquid to puddle, and there was some splash from droplets lost.

APPENDIX II

Establishing an Average Droplet

Application of this program to a standard sprinkling system necessitates establishing a standard droplet for the entire sprinkling system. Using materials in Sprinkler Irrigation (33), the following method was adopted.

The optimum sprinkler system shows a triangular distribution pattern (see Figure 27 a,b) in volume/area (inches). Assuming a circular area and multiplying by area can produce a graph of percentage of spray by volume versus distance spray travels as in Figure 24 c. Note that not only is one half the maximum distance sprayed the average distance, it is also the area where the greatest volume falls. Therefore, the droplet size measured at this point should be appropriate for the entire system. This size could either be measured directly, or Frost and Schwalen's (36) graphs could be used (Figure 28) as in Sprinkler Irrigation. Likewise, data generated by Kohl's (31) research can be used. Low sprinkler pressure systems will bias toward a larger droplet, high sprinkler pressure toward a smaller (36).

There is occasional mention in literature of a "wind drift" (13, 14) factor: a certain amount of moisture discharged in very small droplet form which may or may not eventually settle. This method of average droplet determination does not allow for such a phenomenon. If such exists and is significantly different, it would be necessary to measure and treat this fraction separately (see main text: Conclusions).

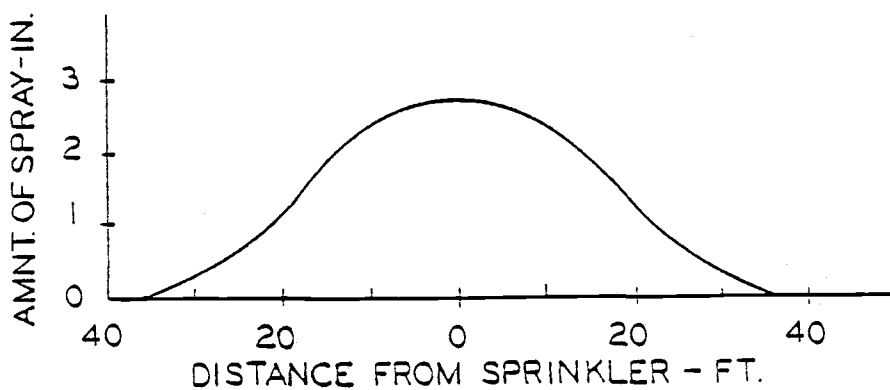


Figure 27a. Typical spray pattern.

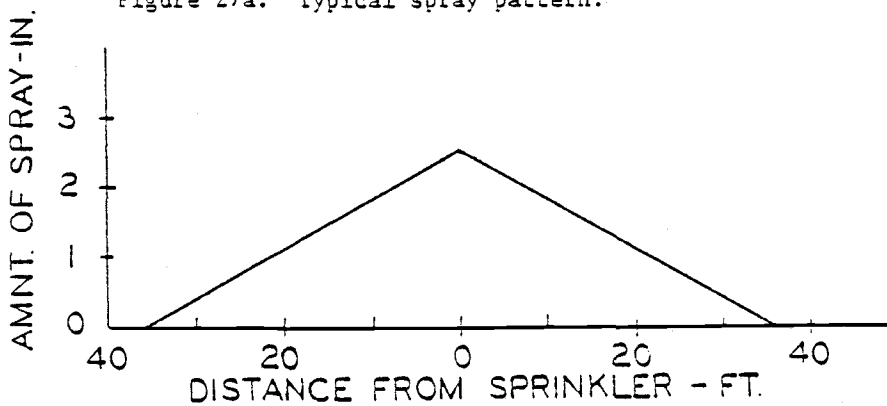


Figure 27b. Typical spray pattern--idealized form.

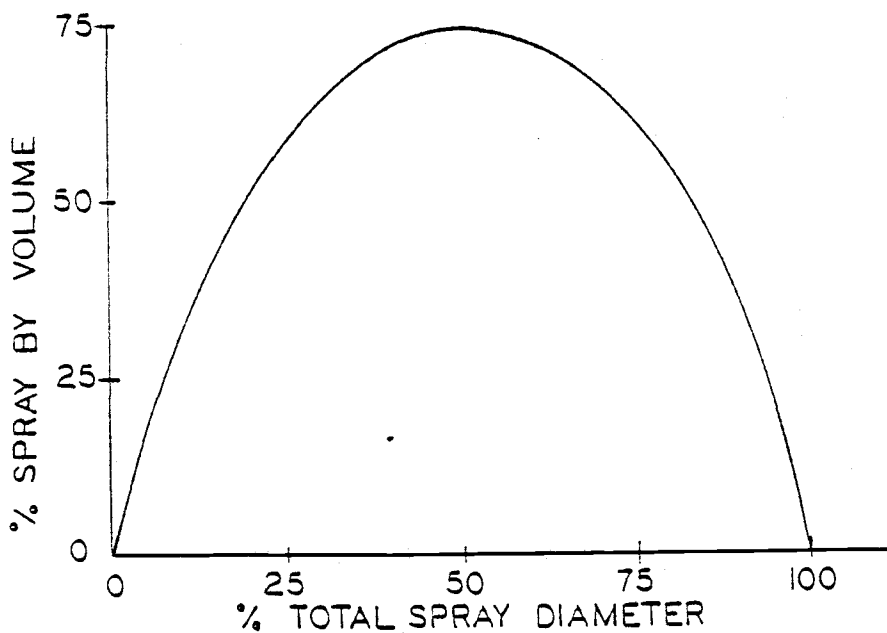


Figure 27c. Typical spray pattern--volume vs. distance.

Figure 27. Analysis of "average" droplet.

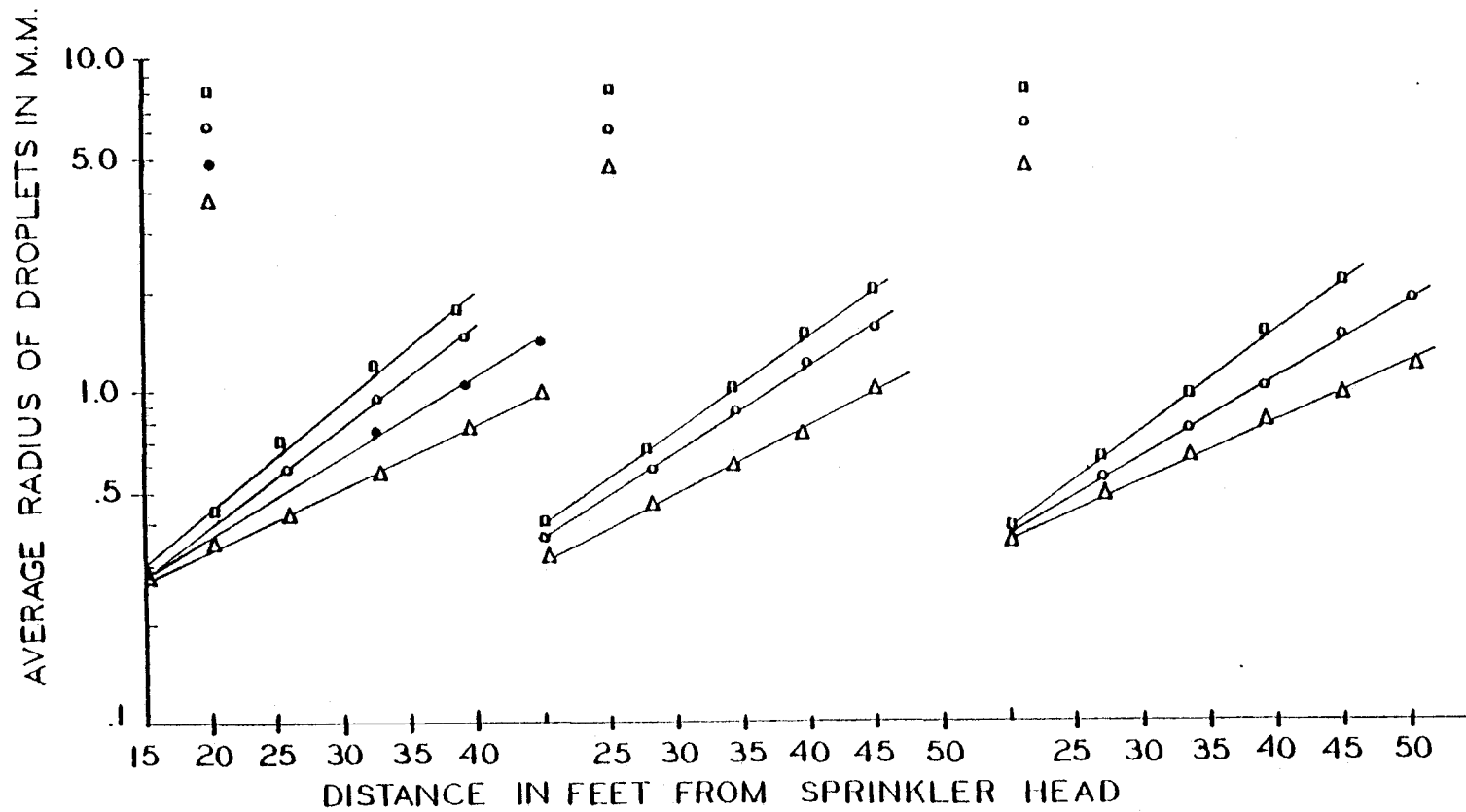


Figure 28. Relationship of droplet size to pressure, nozzle diameter, and distance (from Ref. 33).

APPENDIX III-A

Changes in Parameters During Spraying: Raw Data

Date	Ambient Air Temp.	Parameter	Concentration at Source (mg/l)	Concentration in Field Collectors (mg/l)	Near Spray (mg/l)	Far Spray (mg/l)
7/16	74°F	NH ₃ -N	224.4	---	224.0	223.7
		TDS	1240	1124		
		VDS	500	568		
		TSS	1740	1416		
		VSS	1140	836		
		pH	7.1	7.0		
7/20	72°F	NH ₃ -N	215.0	---	214.7	210.9
		TKN	247	235		
		COD	1354	675		
		PO ₄ -P	77	59		
		TDS	780	764		
		VDS	180	220		
		TSS	1360	1344		
		VSS	900	752		
7/22	70°F	NH ₃ -N	240.3	---	240.1	255.7
		TKN	470	399		
		COD	951	857		
		PO ₄ -P	130	112		
		TDS	1080	948		
		VDS	400	400		
		TSS	508	568		
		VSS	336	392		
		pH	7.1	7.0		

At this point, the system was changed to the second form.

Appendix III-A (continued)

Date	Ambient Air Temp.	Parameter	Concentration at Source (mg/l)	Concentration in Field Collectors (mg/l)	Near Spray (mg/l)	Far Spray (mg/l)
7/31	62°F	NH ₃ -N	174.1	---	174.0	173.9
		TKN	177	179		
		COD	439	447		
		PO ₄ -P	39	50		
		TDS	542	568		
		VDS	132	128		
		TSS	46	71		
		VSS	40	50		
		pH	6.9	7.0		
8/1	72°F	NH ₃ -N	72.42	---	72.24	72.16
8/2	74°F	NH ₃ -N	87.66	---	87.36	87.59
		pH	7.0	7.0		
8/3	66°F	NH ₃ -N	104.37	---	104.16	104.37
		TKN	124	123		
		COD	515	462		
		PO ₄ -P	46	44		
		TDS	546	647		
		VDS	136	139		
		TSS	188	180		
		VSS	140	161		
8/7	94°F	NH ₃ -N	108.08	---	107.89	43.12
		TKN	114	117		
		COD	497	459		
		PO ₄ -P	46	49		
		TDS	606	681		
		VDS	168	169		
		TSS	116	51		
		VSS	92	43		

Appendix III-A (continued)

Date	Ambient Air Temp.	Parameter	Concentration at Source (mg/l)	Concentration in Field Collectors (mg/l)	Near Spray (mg/l)	Far Spray (mg/l)
8/8	76°F	NH ₃ -N	114.10	---	114.05	113.94
		pH	7.1	7.0		
8/9	94°F	NH ₃ -N	177.2	---	176.8	175.5
		TKN	208	199		
		COD	431	470		
		PO ₄ -P	47	58		
		TDS	693	639		
		VDS	205	205		
		TSS	115	115		
		VSS	74	74		
8/10	88°F	NH ₃ -N	69.03	---	68.99	68.84
8/11	68°F	NH ₃ -N	59.56			
		TKN	67	69		
		COD	425	463		
		PO ₄ -P	26	22		
		TDS	337	361		
		VDS	97	84		
		TSS	175	142		
		VSS	138	120		
		pH	6.9	7.0		
8/14	78°F	NH ₃ -N	68.70	---	68.77	68.43
		TKN	79	81		
		COD	294	294		
		PO ₄ -P	30	25		
		TDS	492	481		
		VDS	156	140		
		TSS	98	87		

Appendix III-A (continued)

Date	Ambient Air Temp.	Parameter	Concentration at Source (mg/l)	Concentration in Field Collector (mg/l)	Near Spray (mg/l)	Far Spray (mg/l)
8/15	80°F	VSS	88	85		
		NH ₃ -N	60.43	---	60.48	62.55
		TKN	75	78		
		COD	465	436		
		PO ₄ -P	49	43		
		TDS	376	358		
		VDS	106	104		
		TSS	94	94		
		VSS	84	79		
8/16	70°F	NH ₃ -N	79.26	---	78.96	79.08
		pH	7.0	6.9		
8/17	78°F	NH ₃ -N	99.27	---	99.31	99.26
8/21	58°F	NH ₃ -N	67.68	---	67.57	67.74
8/23	50°F	NH ₃ -N	71.05	---	71.12	70.91
8/24	56°F	NH ₃ -N	68.70	---	68.77	68.43
		TKN	94	93		
		COD	380	376		
		PO ₄ -P	33	33		
		TDS	500	478		
		VDS	168	129		
		TSS	68	67		
		VSS	60	63		
		pH	7.0	7.0		
8/29	74°F	NH ₃ -N	85.02	---	84.90	84.11
		TKN	105	100		
		COD	679	654		
		PO ₄ -P	33	41		

Appendix III-A (continued)

Date	Ambient Air Temp.	Parameter	Concentration at Source (mg/l)	Concentration in Field Collector (mg/l)	Near Spray (mg/10)	Far Spray (mg/l)
		TDS	528	529		
		VDS	136	133		
		TSS	220	138		
		VSS	170	137		
8/30	76°F	NH ₃ -N	95.11	---	94.86	92.06
		TKN	105	108		
		COD	673	678		
		PO ₄ -P	34	35		
		TDS	488	488		
		VDS	168	172		
		TSS	196	184		
		VSS	184	174		
9/4	72°F	NH ₃ -N	101.84	---	101.92	101.72
		pH	7.0	7.0		
9/5	76°F	NH ₃ -N	93.65	---	93.41	92.00
9/6	74°F	NH ₃ -N	80.24	---	80.19	91.17
		TKN	89	94		
		COD	307	313		
		PO ₄ -P	46	41		
		TDS	676	651		
		VDS	206	209		
		TSS	64	60		
		VSS	62	60		
9/7	78°F	NH ₃ -N	194	---	192.1	193.8
		TKN	227	221		
		COD	507	526		
		PO ₄ -P	50	61		

Appendix III-A (continued)

Date	Ambient Air Temp.	Parameter	Concentration at Source (mg/l)	Concentration in Field Collector (mg/l)	Near Spray (mg/l)	Far Spray (mg/l)
		TDS	721	695		
		VDS	176	162		
		TSS	73	70		
		VSS	49	46		
		pH	7.1	7.0		
9/12	72°F	NH ₃ -N	107.42	---	107.18	109.13
9/14	82°F	NH ₃ -N	68.42	---	68.32	56.56
		TKN	96	86		
		COD	452	482		
		PO ₄ -P	27	34		
		TDS	333	426		
		VDS	91	98		
		TSS	87	86		
		VSS	68	78		

APPENDIX III-B

Total Coliform Changes During Spraying: Raw Data

Date	Concentration at Source Coliform/100 ml		Concentration in Field Collectors Coliform/100 ml	
	Primary	Duplicate	Primary	Duplicate
9/15	8.4×10^6		11.4×10^6	8.6×10^6
9/18	9.2×10^6	11.1×10^6	8.6×10^6	8.6×10^6
9/19	9.1×10^6	8.3×10^6	6.6×10^6	3.7×10^6
9/20	7.6×10^6	7.3×10^6	6.4×10^6	6.6×10^6
9/21	9.6×10^6	13.0×10^6	9.1×10^6	8.9×10^6

APPENDIX III-C

Ammonia Loss with Herbage: Raw Data

Date	Source (mg/l)	Collector Without Grass (mg/l)	Collector With Grass (mg/l)
9/15	110.81	110.21	103.41
9/18	98.50	98.40	89.64
9/19	103.02	102.39	88.44
9/20	108.86	108.90	93.87
9/21	116.22	115.31	102.96

Appendix IV: Program Listing

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*DROP PREDICTION OF SPRAY DROPLET DECELERATION AND EVAPORATION ***
PROGRAM DROP(INPUT=/80,OUTPUT=/137,TAPE5=INPUT,TAPE6=OUTPUT)
C THIS PROGRAM CALCULATES TRAJECTORIES OF EVAPORATING SPRAY DROPLETS
C PROGRAM DEVELOPED BY AGR. ENGR. DEPT. UNIV. OF MISSOURI, JANUARY 1972
C MODIFIED BY AGR. ENGR. DEPT. OREGON STATE UNIVERSITY, AUGUST 1978
C (VERSION INCLUDES APPROXIMATION OF EVAPORATIVE MASS LOSSES)
REAL KE,KEI,KZ
DIMENSION LR(400)
DIMENSION Y(8),X(8),GA(8),PE(8),XX(4,8),H(9),ZZ1(8),ZZ2(8)
1,ZZ3(8),IFL(7),AR(800),PAR1(8),PAR2(8),PAR3(8),PAR4(8)
COMMON/IZ/TDBF,RH,PATN,WXYMPH,WZMPH,SPRMPH,THETX,THETAZ,CONC,
+ MON,PNOZ,NINT,IPNT,NK,OMAX,XMM,XMV,RINO,PHI,ZRN,WDFH,ZG,VAL,
+ T,TIME,TIME84,SUNNL,PCTLOS,FP
EQUIVALENCE (AXISV,Y(5)),(AXISX,Y(6))
DATA PAR1(1),PAR1(2),PAR1(3),PAR1(4),PAR1(5),PAR1(6),PAR1(7),PAR1
1(8)/465.0,758.26,454.95,348.3,338.0,363.3,644.95,450.0/
DATA PAR2(1),PAR2(2),PAR2(3),PAR2(4),PAR2(5),PAR2(6),PAR2(7),PAR2
1(8)/73.0,74.0,76.0,80.0,80.0,80.0,75.0,72.0/
DATA PAR3(1),PAR3(2),PAR3(3),PAR3(4),PAR3(5),PAR3(6),PAR3(7),PAR3
1(8)/23.16,15.15,13.15,15.16/
DATA PAR4(1),PAR4(2),PAR4(3),PAR4(4),PAR4(5),PAR4(6),PAR4(7),PAR4
1(8)/1.0,1.0,10.0,10.0,10.0,10.0,10.0,10.0/
PI=4.*ATAN(1.)
*
*
1111 CALL INLZ
*
*
KOUNT=8
TRMRK=-1.0E9
SZMRK=-1.0E9
IEND=C
KEEP=1
IFL(1)=-1
1 IFL(2)=-1
2 CALL RKFOUR(NINT,Y,X,GA,PE,XX,H,ZZ1,ZZ2,ZZ3,TIME,FNTS,KEEP,IFL)
3 IFL(4),3,4,5
*
CONTINUE
G=386.
H(1)=6.0001
C INPUT DROPLET CHARACTERISTICS
OILF=0.
DENSD=1.935/12.0**4
C THE FOLLOWING STATEMENTS CONTROL TERMINATION AND PRINTING
OMIN=1.
XMAX=50.*12.
YMAX=50.*12.
IMARD=0
IOUT=2
IPLDT=0
C COMPUTE OTHER INITIAL CONDITIONS
VLRN=SQRT(1.6*PACZ/DENSC)
CMTI=(1.0E-6)*35.37
WDFH=WDHF*12.
OMAXI=OMAX*CMTI
OFIXI=(OILF**0.33333)*OMAXI
OMINI=OMIN*CMTI
BASE=12.0*CMTI
TKEL=((TDBF-32.)/1.8)+273.
TOBR=TDBF+459.4
OV=(9.28E-6*TKEL**1.88)/(2.54*2.54)
DENSA=PATH/(G*635.6*TOBR)
VISCA=(1.0E-7/144.)*EXP(1.258+0.001262*TOBR)
VISCAK=VISCA/DENSA
SNO=OV/VISCAK
PHIR=PHI*PI/180.
WZ=WZMPH*5280./300.
SPEED=SPRMPH*5280./300.
EPS=1.0E-48
C THE FOLLOWING CARDS SIMULATE THE EFFECT OF TURBULENCE
USTAR=(WXYMPH*5280./300.)*0.4/(ALOG(WOH/20)-4.5*(-RINC/(1.-5.*RINC
1)))
WZ=-1.32*USTAR**3*ABS(RINO)**1.5/(0.064*G*ZRN*(1.-18.*RINC)**.75)
C COMPUTE PRESSURE RATIO FROM BROOKERS MODEL
A1=54.6329
A2=12301.688
A3=5.16923
A4=1075.8965
A5=-4.56983
PS=2.71828** (A1-A2/TOBR-A3*ALOG(TOBR))
PV=PS*RH
PXP=PS
TXP=TOBR

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00 205 J=1.10
BB=0.2405*(PXP-PATH)/(0.62194*(A4+A5*(TXP-491.69)))
BP=XP*(A2/TXP**2-A3/TXP)
TX=(BP*TXP -PXP+PV-BB*TJBR)/(BP-BB)
PX=2.71828** (A1-A2/TX-A3*ALOG(TX))
IF (ABS(PXP-PX)).LE.0.001.AND.ABS(TXP-TX).LE.(.1) GC TC 209
PXP=PX
205 TXP=TX
209 PSWB=PX
PAIR=PATH-PV
RATIO=(PSWB-PV)/PAIR
CON1=-2.0*XMV/XMM*DV*DENSA/DENS0*RATIO
CON2=0.6*SNO**0.333333
Y(1)=VLRN*SIN(THETAZ*PI/180.)*COS(THETXH*PI/180.)
Y(3)=SPEED*VLRN*SIN(THETAZ*PI/180.)*SIN(THETXH*PI/180.)
Y(5)=VLRN*COS(THETAZ*PI/180.)
Y(8)=OMAXI
NK=NK+1
IF (NK.EQ.1) WRITE (6,80) DENS0,XMV,OILF,DENSA,VISCA,TOBF,RH,OV,SNO
1,RATIO,WXYMPH,WDF,PHI
IF (NK.EQ.1) WRITE (6,81) ZRN,RING,USTAR,WZ,SPRMPH,THETAZ,THETXH,HON,
1 VLRN,VAI
80 FORMAT(1H1/11X, SIMULATION OF SPRAY DROPLET TRAJECTORIES# /
1 5X, PROGRAM BY AGR. ENGR. DEPT., UNIV. OF MISSOURI, COLUMBIA, MO. # /
1# *** SPRAY LIQUID PROPERTIES# /
2# DENSITY=#,E12.4, LB-SEC2/IN4# /
3# MOLECULAR WEIGHT=#,F5.1 /
4# OIL FRACTION=#,F5.2, (DECIMAL)# /
5# *** AIR PROPERTIES# /
6# DENSITY=#,E12.4, LB-SEC2/IN4# /
7# DYNAMIC VISCOSITY=#,E12.4, LB-SEC/IN2# /
8# DRY BULB TEMP=#,F7.1, DEG F# /
9# REL HUMIDITY=#,F5.2, (DECIMAL)# /
A# *** AIR-LIQUID PROPERTIES# /
1# DIFFUSIVITY=#,E12.4, IN2/SEC# /
2# SCHMIDT NO.=#,F6.3, (DIMENSIONLESS)# /
3# VAPOR PRESSURE RATIO=#,E12.4# /
4# *** APPLICATION PARAMETERS# /
5# HORIZONTAL WIND SPEED=#,F6.1, MPH AT#,F5.1, FT AND#,F6.0,
6# DEG CW FROM X-AXIS# /
81 FORMAT(1/2X, RICHARDSON NO (AT#,F6.2, INCHES)=#,F7.3/
7# USTAR=#,E12.4, IN/SEC# /
8# VERTICAL AIRSPEED=#,E12.4, IN/SEC# /
9# SPRAYER SPEED=#,F5.1, MPH# /
A# LAUNCH ANGLES=#,F6.1, DEG FROM Z-AXIS AND#,F6.1, HORIZ. DEG CW
B FROM X-AXIS# /
1# LAUNCH HEIGHT=#,F6.1, INCHES# /
2# LAUNCH SPEED REL. TO NOZZLE=#,E12.4, IN/SEC# /
3# INDUCED AIR=#,F3.0, (1=YES,0=NO)# /
C THE FOLLOWING SECTION IS FOR CHANGING PARAMETERS
43 WRITE(6,43) TOBF,RH,WXYMPH
FORMAT(1/2 TEMP=#,F6.2, DEG F,RH=#,F4.2, WIND SPEED#,F4.1, MPH#)
IF (IQUIN.EQ.0) WRITE(6,82)
82 FORMAT(1/2X, TIME, SEC XDOT, IN/SEC YDOT, IN/SEC ZCCT, IN/SEC X, INC
1HES Y, INCHES Z, INCHES D, MICRONS REYN. NO. -NH3, MOL
2 -NH3, XLEFT#)
CONTINUE
CCCCC
INTEGRATOR I/O IDENT--X(1)=X0,Y(1)=X(2)=X0,Y(2)=X,X(3)=Y0,
Y(3)=X(4)=Y0,Y(4)=Y,X(5)=Z0,Y(5)=X(6)=Z0,Y(6)=Z,X(7)=VDROP,
Y(7)=OIST,X(8)=ODOT,Y(8)=OIAM
VIA=VLRN*((BASE/Y(8))**0.2)*EXP(-((Y(7)/2.0)**0.67))*VAI
VDROP=SQRT(Y(1)*Y(1)+Y(3)*Y(3)+Y(5)*Y(5))
ARG=(HON-Y(6))/Z0
WXY=0.
IF (ARG.GT.1.) WXY=2.5*USTAR*(ALOG(ARG)+4.5*RINO/(1.-5.*RINO))
WX=WXY*COS(PHIR)
WY=WXY*SIN(PHIR)
WZ1=WZ+VIA*Y(1)/VDROP
WY1=WY+VIA*Y(3)/VDROP
WZ1=WZ+VIA*Y(5)/VDROP
VREL=SQRT((WX1-Y(1))**2+(WY1-Y(3))**2+(WZ1-Y(5))**2)
REYN=VREL*Y(8)/VISCAK
CD=24./(REYN*EPS)
IF (REYN.GE.0.5) CD=(26.38/REYN**0.845)+0.49
DRAG=PI/8.*DENSA*CD*VREL*VREL*Y(8)*Y(8)
ODOT=CON1/Y(8)*(2.+CON2*REYN**0.5)
IF (Y(8).LE.DFIXI) ODOT=0.
DPEF=DENS0*PI/2.*ODOT*Y(8)*Y(8)*VREL+DRAG
XMASS=PI/6.*Y(8)**3*DENS0

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X(1)=OPEF*(WX1-Y(1))/(XMASS*VREL)
X(2)=Y(1)
X(3)=OPEF*(WY1-Y(3))/(XMASS*VREL)
X(4)=Y(3)
X(5)=(OPEF*(WZ1-Y(5))/(XMASS*VREL))+G
X(6)=Y(5)
X(7)=VDROP
X(8)=DDOT
GO TO 2
CONTINUE

5
ZMAX=MON-ZO-0.25
IF(Y(2).GE.XMAX.OR.Y(4).GE.YMAX) IEND=1
IF(REYN.GT.0.5.AND.IMARD.NE.0) IEND=0
IF(Y(8).LE.DMINI.CR.Y(6).GE.ZMAX) IEND=1
DELT=Y(7)-TRMRK
DELSZ=ABS(Y(8)-SZMRK)
TRMIN=0.1*Y(7)
SZMIN=CMTI
IF(TRMIN.LT.0.5) TRMIN=.5
IF(TRMIN.GT.20.) TRMIN=20.
IF(DELTR.LT.TRMIN.AND.DELSZ.LT.SZMIN.AND.IEND.NE.1) GO TO 16
KOUNT=KOUNT+1
IF(KOUNT.LT.IOUT.ANC.KOUNT.NE.1.AND.IEND.NE.1) GO TO 16
DOU=Y(8)/CMTI
IF(IOUT.EQ.0) GOTO 245
CALL NH3LOS(FP,TKEL,PAT*6891.156,REYN,DMAX/1.E6,CGNC,
+PI,TIME,TIME34,SUMNL,PCTLOS)
WRITE(6,32)TIME,Y(1),Y(3),Y(5),Y(2),Y(4),Y(6),DOU,REYN,
+SUMNL,PCTLOS
245 TRMRK=Y(7)
SZMRK=Y(8)
KOUNT=1
32 FORMAT(1X,11E12.4)
1E CONTINUE

NPL=1
IF(IPLT.NE.0)NPL=IPLT*(KOUNT/IPLT)-KOUNT
IF(IEND.EQ.0) GO TO 1
IF(REYN.GT.0.5.OR.VIA.GE.1.0) GO TO 60
XNU=2.+CON2*REYN**0.5
DELT=0.1
KEI=ABS(DDOT*Y(8))
KE=KEI
KZ=G*(DENSD-OENSA)/(18.*VISCA)
TO=TIME
T=TO
IEND=0
66 WRITE(6,66)
FORMAT(/Z BEGIN SMALL REYNOLDS NUMBER SIMULATIONZ)
ZI=Y(6)
YDIST=Y(4)
XOIST=Y(2)
XMARK=Y(2)
YMARK=Y(4)
DMARK=Y(8)/CMTI
DIAO=Y(8)
47 SIF=0.5
T=T+DELT
DIA=0.
IF((DIAO*DIAO-2.*KE*(T-TO)).GT.0.)DIA=SQRT(DIAO*DIAO-2.*KE*(T-TO))
ZDOT=KZ*DIA*DIA+WZ
ZDIST=ZI+WZ*(T-TO)+KZ*(DIAO*DIAO+2.*KE*TO)*(T-TO)-KE*(T*T-TO*TO)
DOU=DIA/CMTI
WXY=0.
IF((MON-ZDIST).GT.ZO)
1 WXY=2.5*USTAR*(ALOG((MON-ZOIST)/ZO)+4.5*RINO/(1.-5.*RINC))
XDOT=WXY*COS(PHIR)
YDOT=WXY*SIN(PHIR)
REYN=DIA/VISCAK*ABS(ZDOT-WZ)
KE=KEI/XNU*(2.+CON2*REYN**0.5)
XOIST=XDIST+XDOT*DELT*SIF
YDIST=YDIST+YDOT*DELT*SIF
SIF=1.0
IF(ZDIST.GE.MON.OR.DIA.LE.0.0.OR.T.GE.120.) IEND=1
IF((T-TO-DELT).LE.(1.1*E1T)) GO TO 45
IF((2.*KE*(T+DELT-TO)).GE.(DIAO*DIAO)) GO TO 45
DELT=XOIST-XMARK
DELT=YDIST-YMARK
DELT=ABS(DOUB-DMARK)
TRG=600.
IF(DELT.LT.TRG.AND.DELTY.LT.TRG.AND.DELTD.LT.20.(.AND.IEND.EQ.0))
1 GO TO 46
XMARK=XOIST

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```

32 XX(1,I)=XX(3,I)
33 XX(2,I)=XX(4,I)
33 FL(2)=0
   TIME=H(9)+0.5*M(1)
*
34 DO 34 I=1,N
34 Y(I)=XX(1,I)+C1(I)*XX(2,I)
35 KEEP=0
36 FL(4)=0
   RETURN
40 FL(2)=1
*
   DO 41 I=1,N
   XX(3,I)=X(I)
41 Y(I)=XX(1,I)+C1(I)*X(I)
   GO TO 35
45 IF (FL(2)-2) 46,48,68
46 FL(2)=2
   TIME=H(9)+H(1)
*
   DO 47 I=1,N
   XX(4,I)=X(I)
47 Y(I)=XX(1,I)+C2(I)*X(I)
   GO TO 35
48 FL(2)=3
   IF (H(7)) 49,52,52
49 KEEP=FL(6)
*
50 DO 51 I=1,N
51 Y(I)=XX(1,I)+C3(I)*(XX(2,I)+X(I)+2.*(XX(3,I)+XX(4,I)))
   GO TO 36
52 ERR=0.0
*
   DO 56 I=1,N
   ESTERR=C2(I)*ABS(XX(2,I)+X(I)-2.*XX(4,I))
   IF (PEAK(I)) 53,53,54
54 ESTERR=ESTERR/PEAK(I)
53 IF (ERR=ESTERR) 55,56,56
55 ERR=ESTERR
56 CONTINUE
*
57 IF (ERR-H(6)) 57,57,66
58 IF (ERR-H(5)) 58,59,59
58 FL(7)=FL(7)-1
   IF (FL(7)) 65,65,49
65 FL(3)=1
   GO TO 49
59 FL(7)=H(8)
   GO TO 49
66 FL(7)=H(8)
   GO TO 21
60 IF (H(7)) 7,61,61
*
61 DO 63 I=1,N
   ERR=ABS(Y(I))
   IF (ERR-PEAK(I)) 63,63,62
62 PEAK(I)=ERR
63 CONTINUE
*
   GO TO 7
   END
   SUBROUTINE NM3LOS
   (FP,T,P,R,DP,CAL,PI,TNOW,TB4,SUMNL,PCTLCS)
   REAL KC,KD,N1,N2,NL,N11
*
***** NAMELIST/888/T,P,R,DP,DAB,S,KC,KD,CAS,CAL,WA,
***** N1,N11,N2,NL,SUMNL,TB4,TNOW,PH,FP
***** PRINT*,* * * PRINT*,* * *
***** PRINT 888
   IF (TNOW.EQ.0.) RETURN
   IF (TB4.EQ.0.0) SUMNL=0.0
   DAB=4.447E-4*T**1.5/P
   S=11.93/SQRT(T)
   KC=DAB/DP*(2.0+0.952*SQRT(R))*S**(1./3.)
   KD=2.31E-5*T-6.12E-3
   CAS=KD*CAL
   WA=PI*DP*DP*KC*CAS
   NL=WA*(TNOW-TB4)*FP
   N1=CAL*PI*DP**3/6.0
   IF (TB4.EQ.0.0) N11=N1
   N2=N1-NL
***** PRINT 888
   CAL=6.0*N2/(PI*DP**3)

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```

SUMNL=SUMNL+NL
PCTLOS=0.0
IF(N11.NE.0.0.AND.TNOW.GT.0.)PCTLOS=(N11-SUMNL)/N11*100.
TB4=TNOW
***** PRINT BBB
RETURN
END
SUBROUTINE INLZ
*** INITIAL VALUE ROUTINE ***
COMMON/IZ/TOBF,RH,PATM,WXYMPH,WZMPH,SPRMPH,THETXH,THETAZ,CONC,
+ HON,PNOZ,NINT,IPNT,NK,DMAX,XMM,XMV,RIND,PHI,ZRN,WOHF,ZO,VAI,
+ T,TIME,TIMEB4,SUMNL,PCTLOS,FP
NAMELIST/INL/TOBF,RH,FATM,WXYMPH,WZMPH,SPRMPH,THETXH,THETAZ,
+ HON,PNOZ,DMAX,CONC,PH
*
PRINT 100 $ TOBF=50. $ RH=.3 $ PATM=14.7 $ WXYMPH=5. $ DMAX=200.
CONC=WZMPH=THETXH=T=TIME=TIMEB4=SUMNL=PCTLOS=0.
HON=24. $ PNOZ=40. $ SPRMPH=5. $ IPNT=NK=0 $ NINT=8 $ PH=7.
THETAZ=90. $ PRINT INL $ PRINT 100
*
PRINT*,$ IF ANY OF THE ABOVE VALUES ARE ACCEPTABLE,$
PRINT*,$ PRESS <RETURN> KEY ONLY,$ $ PRINT*,$ $
C INPUT ATMOSPHERIC CONDITIONS
XMM=20. $ XMV=18.
PRINT*,$ ENTER TEMPERATURE (DEG F)$
READ*,XXIN
IF(EOF(5LINPUT).EQ.0)TOBF=XXIN
PRINT*,$ ENTER RELATIVE HUMIDITY (X)$
READ*,XXIN
IF(EOF(5LINPUT).EQ.0)RH=XXIN
IF(RH.GT.1.)RH=RH/100.
PRINT*,$ ENTER ATMOSPHERIC PRESSURE (PSI)$
READ*,XXIN
IF(EOF(5LINPUT).EQ.0)PATM=XXIN
PRINT*,$ ENTER WIND SPEED COMPONENTS (MPH)$
PRINT*,$ WXY-MPH$ $ READ*,XXIN
IF(EOF(5LINPUT).EQ.0)WXYMPH=XXIN
PRINT*,$ WZ-MPH$ $ READ*,XXIN
IF(EOF(5LINPUT).EQ.0)WZMPH=XXIN
RIND=PHI=0. $ ZRN=33.37 $ WOHF=6.
C INPUT LAUNCH CONDITIONS
ZO=0.7/2.54
VAI=1
PRINT*,$ ENTER INITIAL SPRAY VELOCITY (MPH)$
READ*,XXIN
IF(EOF(5LINPUT).EQ.0)SPRMPH=XXIN
PRINT*,$ ENTER COMPONENTS OF SPRAY DIRECTION$
PRINT*,$ THETXH$
READ*,XXIN
IF(EOF(5LINPUT).EQ.0)THETXH=XXIN
PRINT*,$ THETAZ$ $ READ*,XXIN
IF(EOF(5LINPUT).EQ.0)THETAZ=XXIN
PRINT*,$ ENTER NOZZLE HEIGHT (INCHES)$
READ*,XXIN
IF(EOF(5LINPUT).EQ.0)HON=XXIN
PRINT*,$ ENTER NOZZLE PRESSURE (PSI)$
READ*,XXIN
IF(EOF(5LINPUT).EQ.0)PNOZ=XXIN
PRINT*,$ ENTER MAXIMUM DROPLET DIAMETER (MM)$
READ*,XXIN
IF(EOF(5LINPUT).EQ.0.AND.XXIN.GT.2.E-3)DMAX=XXIN*1000.
PRINT*,$ ENTER INITIAL MHS CONCENTRATION (MOL/M3)$
READ*,XXIN
IF(EOF(5LINPUT).EQ.0)CONC=XXIN
PRINT*,$ ENTER PH$ $ READ*,XXIN
IF(EOF(5LINPUT).EQ.0)PH=XXIN
FP=1./(10.**(.9.26-PH)+1.)
*
PRINT 100 $ PRINT INL $ PRINT 101
*
RETURN
100 FORMAT(//////1MS)
101 FORMAT(//////1MT)
END

```



```

SUMNL=SUMNL+NL
PCTLOS=0.0
IF (K11.NE.0.0.AND.TNOH.GT.0.)PCTLOS=(N11-SUMNL)/N11*100.
P34=TNOH
***** PRINT 98E
RETURN
END
SUBROUTINE INLZ
*** INITIAL VALUE ROUTINE ***
COMMON/I2/T0BF,RH,PATN,WXYPH,WZMPH,SFRMPH,THETXH,THETAZ,CONC,
+ HUN,PNOZ,NINT,IPNT,NK,OMAA,XMP,XMV,RINC,PHI,ZRN,MOHF,ZC,VAI.
+ T,TIME,TIMEB4,SUMNL,PCTLOS,FP
+ NAMELIST/INL/T0BF,RH,PATN,WXYPH,WZMPH,SFRMPH,THETXH,THETAZ,
+ HUN,PNOZ,OMAX,CONC,PH
*
PRINT 10C 3 T0BF=51. 3 RH=3 3 PATN=16.7 3 WXYPH=9. 3 OM=20.
CONC=2. 3 WZMPH=THEIXHETIT+41ETI4100=SUMNL=PCTLOS=
HUN=24. 3 PNOZ=41. 3 SFRMPH=5. 3 IPNT=NK=9 3 NINT=0 3 PH=7.
THETAZ=90. 3 PRINT INL 3 PRINT 10C
*
PRINT*, 2 IF ANY OF THE ABOVE VALUES ARE ACCEPTABLE, 2
PRINT*, 2 PRESS <RETURN> KEY ONLY 2 PRINT*, 2
C INPUT ATMOSPHERIC CONDITIONS
VAI=25. 3 XMP=13.
PRINT*, 2 ENTER TEMPERATURE (DEG F) 2
READ*, XXIN
IF (EOF(SLINPUI).EQ.0)T0BF=XXIN
PRINT*, 2 ENTER RELATIVE HUMIDITY (%) 2
READ*, XXIN
IF (EOF(SLINPUI).EQ.0)RH=XXIN
IF (RH.GT.1.)RH=RH/100.
PRINT*, 2 ENTER ATMOSPHERIC PRESSURE (PSI) 2
READ*, XXIN
IF (EOF(SLINPUI).EQ.0)PATN=XXIN
PRINT*, 2 ENTER WIND SPEED COMPONENTS (MPH) 2
PRINT*, 2 WXY=MPH 2 3 READ*, XXIN
IF (EOF(SLINPUI).EQ.0)WXYPH=XXIN
PRINT*, 2 WZ=MPH 2 3 READ*, XXIN
IF (EOF(SLINPUI).EQ.0)WZMPH=XXIN
XINO=PHI=0. 3 ZRN=39.37 3 MOHF=6.
C INPUT LAUNCH CONDITIONS
ZC=0.772.54
VAI=1
PRINT*, 2 ENTER INITIAL SPRAY VELOCITY (MPH) 2
READ*, XXIN
IF (EOF(SLINPUI).EQ.0)SPRMPH=XXIN
PRINT*, 2 ENTER COMPONENTS OF SPRAY DIRECTION 2
PRINT*, 2 THETXH 2
READ*, XXIN
IF (EOF(SLINPUI).EQ.0)THETXH=XXIN
PRINT*, 2 THETAZ 2 3 READ*, XXIN
IF (EOF(SLINPUI).EQ.0)THETAZ=XXIN
PRINT*, 2 ENTER NOZZLE HEIGHT (INCHES) 2
READ*, XXIN
IF (EOF(SLINPUI).EQ.0)HON=XXIN
PRINT*, 2 ENTER NOZZLE PRESSURE (PSI) 2
READ*, XXIN
IF (EOF(SLINPUI).EQ.0)PNOZ=XXIN
PRINT*, 2 ENTER MAXIMUM DROPLET DIAMETER (MM) 2
READ*, XXIN
IF (EOF(SLINPUI).EQ.0.AND.XXIN.GT.2.E-3)OMAX=XXIN*1000.
PRINT*, 2 ENTER INITIAL NH3 CONCENTRATION (MCL/M3) 2
READ*, XXIN
IF (EOF(SLINPUI).EQ.0)CONC=XXIN
PRINT*, 2 ENTER PH 2 3 READ*, XXIN
IF (EOF(SLINPUI).EQ.0)PH=XXIN
SP=1./(10.**((9.26-PH)+1.))
*
PRINT 10C 3 PRINT INL 3 PRINT 101
*
RETURN
100 FORMAT(//////1HS)
101 FORMAT(//////1HT)
END

```

19.33.55.UCLP, 4A22,

0.541KLS.

Appendix V: Sample Run of Program

79/02/22. 11.29.30. OSU 1.14.6
NOS 1.3
USER NUMBER: adja5c
PASSWORD
■■■■■■■■
TERMINAL: 26, TTY
RECOVER/ CHARGE: +DEL+
bye
ADJA5C LOG OFF 11.30.19.
ADJA5C SRU 0.625 UNITS.

79/02/22. 13.00.30. OSU 1.14.6
NOS 1.3
USER NUMBER: adja5c
PASSWORD
■■■■■■■■
TERMINAL: 11, TTY
RECOVER/ CHARGE: recover
RECOVERY COMPLETE.
LAST COMMAND = HANG
JOB STATUS = IDLE
NEXT OPERATION = ENTER COMMAND
ENTER +CR+ TO CONTINUE:
/old/go
/call,go

```
$INL  
TDRF = .5E+02,  
RH = .3E+00,  
FATM = .147E+02,  
WXYZFH = .5E+01,  
WZMFH = 0.0,  
SERMFH = .5E+01,  
THETXU = 0.0,  
THETAZ = .9E+02,  
HON = .24E+02,  
FNOZ = .4E+02,  
DMAX = .2E+03,  
CONC = 0.0,  
FH = .7E+01,  
$END
```

IF ANY OF THE ABOVE VALUES ARE ACCEPTABLE,
PRESS <RETURN> KEY ONLY

ENTER TEMPERATURE (DEG F)

? 90

ENTER RELATIVE HUMIDITY (Z)

? 20

ENTER ATMOSPHERIC PRESSURE (FSI)

?

ENTER WIND SPEED COMPONENTS (MPH)

WXY-NFH

?

WZ-MPH

?

ENTER INITIAL SPRAY VELOCITY (MPH)

? 34.22

ENTER COMPONENTS OF SPRAY DIRECTION

THETX

? 0

THETAZ

? 120

ENTER NOZZLE HEIGHT (INCHES)

? 19

ENTER NOZZLE PRESSURE (FSI)

?

ENTER MAXIMUM DROPLET DIAMETER (MM)

? 2.76

ENTER INITIAL NH3 CONCENTRATION (MOL/M3)

? 5

ENTER PH

? 9

```
$INL  
TDBF = .9E+02,  
RH = .2E+00,  
PAIN = .147E+02,  
UXYRPH = .5E+01,  
UZNRPH = 0.0,  
SFRMRPH = .3422E+02,  
THETX = 0.0,  
THETAZ = .12E+03,  
HON = .19E+02,  
FNOZ = .4E+02,  
INAX = .276E+04,  
CONC = .5E+01,  
PH = .9E+01,  
$END
```

SIMULATION OF SPRAY DROPLET TRAJECTORIES
PROGRAM BY AGR. ENGR. DEPT., UNIV. OF MISSOURI, COLUMBIA, MO.

***SPRAY LIQUID PROPERTIES
DENSITY= .933E-04 LB-SEC²/IN⁴
MOLECULAR WEIGHT= 18.0
OIL FRACTION= 0.00 (DECIMAL)

***AIR PROPERTIES
DENSITY= .1084E-06 LB-SEC²/IN⁴
DYNAMIC VISCOSITY= .2737E-08 LB-SEC/IN²
DRY BULB TEMP= 90.0 DEG F
REL HUMIDITY= .20 (DECIMAL)

***AIR-LIQUID PROPERTIES
DIFFUSIVITY= .3837E-01 IN²/SEC
SCHMIDT NO.= 1.519 (DIMENSIONLESS)
VAPOR PRESSURE RATIO= .9800E-02

***APPLICATION PARAMETERS
HORIZONTAL WIND SPEED= 5.0 MPH AT 6.0 FT AND 0. DEG CW FROM X-AXIS

RICHARDSON NO (AT 39.37 INCHES)= 0.000
USTAR= .6325E+01 IN/SEC
VERTICAL AIRSPEED= 0. IN/SEC
SPRAYER SPEED= 34.2 MPH
LAUNCH ANGLE= 120.0 DEG FROM Z-AXIS AND 0.0 HORIZ. DEG CW FROM X-AXIS
LAUNCH HEIGHT= 19.0 INCHES
LAUNCH SPEED REL. TO NOZZLE= .8282E+03 IN/SEC
INDUCED AIR= 1. (1=YES,0=NO)

TEMP= 90.00 DEG F, RH= .20 WIND SPEED 5.0 MPH

TIME-SEC	XWOT, IN/SEC	YUOT, IN/SEC	ZUOT, IN/SEC	X, INCHES	Y, INCHES	Z, INCHES	U, MICRONS	REYN. NO.	-NH3, MOL	-NH3, ZLEFT
0.	.7172E+03	.6023E+03	-.4141E+03	0.	0.	0.	.2760E+04	.3010E+04	0.	0.
.5414E-03	.7164E+03	.6015E+03	-.4133E+03	.3881E+00	.3259E+00	-.2240E+00	.2760E+04	.3417E+04	.5516E-11	.9999E+02
.1424E-02	.7147E+03	.5998E+03	-.4119E+03	.1020E+01	.8563E+00	-.5803E+00	.2760E+04	.3654E+04	.1480E-10	.9997E+02
.1990E-02	.7136E+03	.5988E+03	-.4110E+03	.1424E+01	.1195E+01	-.8210E+00	.2760E+04	.3745E+04	.2081E-10	.9996E+02
.2790E-02	.7119E+03	.5973E+03	-.4094E+03	.1994E+01	.1674E+01	-.1149E+01	.2760E+04	.3832E+04	.2941E-10	.9995E+02
.3921E-02	.7094E+03	.5949E+03	-.4075E+03	.2798E+01	.2348E+01	-.1611E+01	.2760E+04	.3907E+04	.4167E-10	.9992E+02
.5521E-02	.7057E+03	.5915E+03	-.4045E+03	.3930E+01	.3297E+01	-.2261E+01	.2760E+04	.3962E+04	.5913E-10	.9989E+02
.7784E-02	.7005E+03	.5866E+03	-.4003E+03	.5521E+01	.4630E+01	-.3172E+01	.2760E+04	.3989E+04	.8389E-10	.9985E+02
.1098E-01	.6929E+03	.5796E+03	-.3943E+03	.7751E+01	.6496E+01	-.4443E+01	.2760E+04	.3982E+04	.1189E-09	.9978E+02
.1551E-01	.6825E+03	.5698E+03	-.3860E+03	.1086E+02	.9097E+01	-.6209E+01	.2760E+04	.3934E+04	.1680E-09	.9969E+02
.2191E-01	.6681E+03	.5565E+03	-.3745E+03	.1518E+02	.1270E+02	-.8642E+01	.2760E+04	.3849E+04	.2367E-09	.9957E+02
.3096E-01	.6490E+03	.5385E+03	-.3589E+03	.2114E+02	.1766E+02	-.1194E+02	.2760E+04	.3720E+04	.3323E-09	.9940E+02
.4376E-01	.6240E+03	.5150E+03	-.3385E+03	.2929E+02	.2440E+02	-.1642E+02	.2760E+04	.3545E+04	.4641E-09	.9914E+02
.6186E-01	.5923E+03	.4852E+03	-.3120E+03	.4029E+02	.3344E+02	-.2231E+02	.2760E+04	.3321E+04	.6446E-09	.9883E+02
.8746E-01	.5537E+03	.4485E+03	-.2789E+03	.5495E+02	.4538E+02	-.2986E+02	.2760E+04	.3044E+04	.8889E-09	.9796E+02
.1131E+00	.5207E+03	.4171E+03	-.2499E+03	.6869E+02	.5645E+02	-.3662E+02	.2759E+04	.2811E+04	.1123E-08	.9755E+02
.1387E+00	.4922E+03	.3899E+03	-.2240E+03	.8164E+02	.6677E+02	-.4268E+02	.2759E+04	.2608E+04	.1348E-08	.9755E+02
.1643E+00	.4675E+03	.3661E+03	-.2008E+03	.9392E+02	.7644E+02	-.4811E+02	.2759E+04	.2430E+04	.1566E-08	.9716E+02
.1899E+00	.4457E+03	.3451E+03	-.1797E+03	.1054E+03	.8554E+02	-.5298E+02	.2759E+04	.2273E+04	.1775E-08	.9677E+02
.2411E+00	.4092E+03	.3098E+03	-.1425E+03	.1273E+03	.1023E+03	-.6120E+02	.2759E+04	.2007E+04	.2170E-08	.9606E+02
.3135E+00	.3692E+03	.2709E+03	-.9844E+02	.1556E+03	.1232E+03	-.6988E+02	.2759E+04	.1722E+04	.2487E-08	.9512E+02
.4733E+00	.3096E+03	.2409E+03	-.6114E+02	.1811E+03	.1417E+03	-.7562E+02	.2758E+04	.1504E+04	.3168E-08	.9424E+02
.5757E+00	.2833E+03	.2126E+03	-.2220E+02	.2094E+03	.1615E+03	-.7922E+02	.2758E+04	.1309E+04	.3708E-08	.9326E+02
.6781E+00	.2623E+03	.1868E+03	-.1762E+02	.2397E+03	.1819E+03	-.7941E+02	.2757E+04	.1149E+04	.4299E-08	.9219E+02
.7505E+00	.2495E+03	.1537E+03	-.7592E+02	.2676E+03	.2115E+03	-.7109E+02	.2757E+04	.1002E+04	.4860E-08	.9047E+02
.8229E+00	.2380E+03	.1425E+03	-.5300E+02	.3038E+03	.2222E+03	-.6481E+02	.2757E+04	.9759E+03	.5244E-08	.8979E+02
.8953E+00	.2274E+03	.1321E+03	-.1173E+03	.3306E+03	.2322E+03	-.5703E+02	.2757E+04	.9651E+03	.5421E-08	.8911E+02
.9877E+00	.2174E+03	.1229E+03	-.1358E+03	.3367E+03	.2414E+03	-.4785E+02	.2756E+04	.9666E+03	.6364E-08	.8844E+02
.1070E+01	.2041E+03	.1104E+03	-.1597E+03	.3583E+03	.2533E+03	-.3270E+02	.2756E+04	.9841E+03	.6887E-08	.8749E+02
.1173E+01	.1914E+03	.9925E+02	-.1808E+03	.3785E+03	.2641E+03	-.1524E+02	.2755E+04	.1015E+04	.7411E-08	.8653E+02
.1275E+01	.1786E+03	.8877E+02	-.1991E+03	.3975E+03	.2737E+03	-.4244E+01	.2755E+04	.1060E+04	.7941E-08	.8557E+02
.1377E+01	.1628E+03	.7879E+02	-.2140E+03	.4150E+03	.2822E+03	-.2543E+02	.2755E+04	.1203E+04	.8494E-08	.8457E+02

TYPE <RETURN> TO STOP

?

VITA

Third of fourteen children, Jonathan Woodrome Pote was born March 3, 1953 in Seligman, Arizona. Six years later his family moved to Arkansas, and in 1971 he graduated from Watson Chapel High School in Pine Bluff, Arkansas.

The author entered Hendrix College in Conway, Arkansas, in the fall of 1971 and during his junior year married Linda Marie Wayland. In June of 1975 he graduated with a Bachelor of Science degree in Chemistry. His summer job as a ranger with the Corps of Engineers on the north Arkansas rivers and lakes contributed to his interest in the area of water resources.

From 1975 to 1977 he and his wife were Peace Corps volunteers teaching at Fletcher College in Belize, Central America.

At the close of their service they entered graduate school at Oregon State University. He pursued a Master of Science degree in Civil Engineering in the area of environmental engineering while serving as a Graduate Research Assistant for the Department of Agricultural Engineering.