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GRADUATE COLLEGE

ATMOSPHERIC DISPERSION OF PARTICULATE EMISSIONS FROM AN ACTIVATED SLUDGE UNIT

A DISSERTATION

SUBMITTED TO THE GRADUATE FACULTY

in partial fulfillment of the requirements for the

degree of

DOCTOR OF PUBLIC HEALTH

BY

ROY M. BUCHAN

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ATMOSPHERIC DISPERSION OF PARTICULATE EMISSIONS

FROM AN ACTIVATED SLUDGE UNIT

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CHAPTER I

INTRODUCTION

At the present time the population of the United States is over 200 million people with approximately 73 per cent of the people living in urban areas. It has been projected that by the year 2000 the population will reach 314 million with approximately 85 per cent of this total living in large metropolitan areas (1). It is obvious that this increase of humanity in relatively confined areas will place unprecedented stress upon sewage treatment facilities. Waste water treatment facilities, such as the activated sludge unit, that are suited for treating large continuous urban loads quickly and efficiently will undoubtedly have to be more widely used.

Waste water treatment by an activated sludge unit involves the aerobic biological oxidation of organic matter in the presence of agitation and excess oxygen. Processing efficiency is increased by "activated sludge", collected from secondary sedimentation, and recirculated into the aeration basin (2). The air injection and agitation of this treatment process provides a means for bacteria and particulates to be emitted into the air from the unit and thus contribute to the air pollution prob-

lems of an urban area (3).

Sewage, no matter how well treated, may contain pathogenic bacteria (4). If pathogens emitted from an activated sludge unit are inhaled by a susceptible host it is obvious that illness may occur. The potential health effects of particles emitted from the unit are both indirect and direct. Indirectly the particles can provide a means for bacteria to be carried through the air and into the lungs, also the particles can provide a surface for water to adhere to and keep the vegetative bacterial cell viable (5). Due to the innate composition of domestic sewage the possibility of protein type particles being emitted is great, and if inhaled these particles could directly initiate an allergic response (6).

The bacteria and particulates emitted from the activated sludge unit can have no effect upon health unless they are transmitted from the unit to a susceptible host. Thus an understanding of the transmission of the bacteria and particulates through the air is essential to understanding the magnitude of the activated sludge unit as a primary air pollution source. Those parameters that must be considered in evaluating air transport and dispersion from the source are: fall rate of the bacteria or particle, windspeed, wind direction, atmospheric turbulence, and rate of contaminant emissions (7). If these parameters are of sufficient magnitude the particles and bacteria can be carried great distances, not just affecting the health and well-being of those employed at the treatment facility, but also affecting the general population living in the vicinity of the sewage treatment plant.

It can be concluded that the activated sludge unit will be used

to a much greater extent in the future to meet the demands of increased urbanization. Since this form of sewage treatment may be a primary air pollution source with emissions of potential danger to the health of plant employees and the general population of large urban areas it was imperative that research be done to evaluate the quantity, quality and atmospheric dispersion of the contaminant emissions of the activated sludge unit.

CHAPTER II

LITERATURE REVIEW

Traditionally air pollution is thought of as a contamination of the atmosphere with smoke, industrial dust, sulfur oxides, hydrocarbons and various other particulates and gases. Rarely considered are the biological contaminants such as spores, pollen grains, bacteria, viruses, fungii, and protein bearing particulates that can be found in the air. Considering the etiology of upper respiratory disease, bacteria cause 8.2 per cent of the respiratory diseases and 19.9 per cent are caused by viruses. The remaining 71.9 per cent of the etiology is unknown (8). It is clearly evident that biological contaminants should be more thoroughly considered as an air pollution entity.

To assay the air and determine what contaminants are present is not enough. For a comprehensive understanding of air pollution and its control, the primary sources of the various contaminants must be located (9). Jensen (10) was the first to suggest sewage treatment processes as a source of bacterial air contamination. Upon evaluating his data on the survival of the tubercule bacillus in liquid phases of sewage treatment processes he suggested that such processes may provide a danger of tuberculosis infection to plant employees from droplets injected into the air by activated sludge units, trickling filters, and by wind action on

waste water surfaces.

Randall and Ledbetter (3) stated that Wells and Fair were the first to study bacterial emissions into the air by sewage disposal units. From their restricted investigation they concluded bacterial contamination of the atmosphere by sewage works exists and that liberated organisms of respiratory and skin diseases could remain airborne and viable for long periods of time.

In studying air pollution from waste water treatment facilities, Albrect (11) determined that increased numbers of bacteria downwind from a trickling filter were directly correlated to increased wind velocity. He surmised residents in the area of such facilities were at risk of infection if winds and bacterial emissions were of sufficient magnitude.

Naplitano and Rowe (12) compared the numbers of coliform organisms downwind from activated sludge units and high rate trickling filter plants. The investigation was limited to collecting organisms for 5-minute periods using Anderson sieve samplers. They found that the number of coliforms downwind from the aeration basins of the activated sludge units was ten times the number found downwind from the high rate trickling filters.

Ladd (13) sampled airborne bacteria around preaeration tanks, trickling filters and activated sludge units. He found that bacterial counts downwind from these units were consistently higher than the ambient air counts. He also observed that sewage flow, ambient temperature, windspeed and relative humidity affected the bacterial concentrations downwind from the units. Ladd used a bacterial tracer organism, Bacillus subtilis var. globgii, and found that a known bacteria could be added to

the influent and collected in the air downwind from a preaeration tank. He concluded that pathogens could be emitted from such treatment units, and could be harmful to plant operators or others living close to the treatment facilities.

Randall and Ledbetter (3) conducted an investigation into the bacteria emitted from the activated sludge unit. They found the bacteria count upwind from the unit to be 8 per ft^3 and 1170 per ft^3 on the downwind slide. Despite a rapid die-off of bacteria during the first 3 seconds they are airborne, it was observed that the population persists for a considerable time and distance. They also noted that 19 per cent of the bacterial concentrations downwind from the unit were Klebsiella sp., some of which were proven pathogens of the respiratory tract. They also noted that Klebsiella sp. could serve as indicators of bacterial air pollution from sewage sources. It was concluded that there is a definite possibility of airborne infection from sludge units.

King (14) conducted a comprehensive investigation into the dispersion of bacterial organisms into the ambient air from an activated sludge unit by identifying bacteria common to the aeration tanks of the plant and isolating these same bacteria downwind. At a distance of 100 ft from the aeration gallery he isolated as many as 1,472 colonies per ft^3, while upwind the control sample produced only 14 colonies for the same sampling period. While no proven pathogens were isolated he did isolate organisms having similar properties to primary pathogens and suggested the plant personnel and residents in the area may be facing a potential health hazard. He also utilized a tracer organism, Serratia marcesens, and found that the organisms could be introduced into the

aeration gallery and later be collected downwind from the unit, thus firming his hypothesis that bacteria are readily emitted from activated sludge units.

It has been well established that bacterial pathogens may be emitted from sewage disposal units. Due to the less obvious effect upon health, particulate emissions have not been studied as thoroughly. Wells (15) contends that particles play an important role in bacterial airborne transmission for particles may provide a moist environment for the vegetative bacterial cells to remain viable in air transport. Brown et al. (16) investigated the influence of particle size upon the retention of particles in the human lung. It was determined that particulates having diameters in the 10- to 100-micron range were efficiently filtered in nasopharyngeal region, while particles in the 0.1- to 10-micron range were effectively retained in the lungs and particles less than 0.1-micron were exhaled. Randall and Ledbetter (3) observed that particles emitted from activated sludge units were predominately in the lung penetrating range. They concluded that the particles could play an important role in carrying bacteria into the lungs.

In general it can be stated that of the solids in sewage approximately 40 per cent is organic. Of the organics present proteins constitute 40 per cent and carbohydrates and lipids make up 50 per cent and 10 per cent, respectively (2). Benack (17) points out the most allergenic reactions are initiated by antigens of protein composition, but it is also known that certain carbohydrates and lipid substances have some antigenic ability. He also notes that about 10 per cent of the U.S. population suffers from diagnosed allergies and that possibly 50 per cent

of the population could suffer from undiagnosed minor allergies. It can be seen that should proteinaceous particulate matter be emitted from an activated sludge unit it may be allergenic to plant operators or residents in the area if such particles are inhaled.

To adequately understand the significance of activated sludge units as air pollution sources, with their emission of bacteria and particulates, it is essential to comprehend the atmospheric dispersion associated with the units. Those parameters which affect dispersion can be divided into two major categories, source factors and meteorological factors (9).

Classically source factors include such parameters as stack height, stack velocity, stack diameter, and emission rate (9). In comparing these factors to the activated sludge unit, stack height can be neglected as the activated sludge unit is a ground level source. Stack velocity can also be eliminated as an important parameter since the stack velocity in this instance approaches zero and is negligible. This leaves only two source factors of importance when considering dispersion from an activated sludge unit; emission rate and the stack diameter which can be considered in this case as analogous to the surface area of the aeration basin.

The meteorological factors affecting dispersion include windspeed, wind direction, and atmospheric turbulence which is dependent upon atmospheric stability, i.e., vertical wind profile and vertical temperature structure (18). In contrast to the source factors, none of the meteorological parameters can be neglected in respect to dispersion from an activated sludge unit. Obviously windspeed and wind di-

rection will effect where and at what rate the contaminants are carried and dispersed. Atmospheric turbulence plays the dominant role in determining the rate of diffusion. It can be stated in general that as turbulence increases the rate of diffusion or spreading and dilution of the plume increases. As the vertical temperature structure approaches the dry adiabatic lapse rate, turbulence increases. Likewise, as the vertical wind profile intensifies, turbulence increases (19).

Sutton of Great Britain is credited with the initial mathematical description of atmospheric dispersion. Sutton's equations are quite complicated and not of practical use in most field investigations as they require extensive data from sophisticated meteorological equipment (19). Since Sutton first derived his equations in 1932 considerable progress has been made in developing equations that are amenable to field situations. A major development occurred in 1957 when Hay and Pasquill (20) empirically demonstrated that the vertical distribution of particles from an elevated source is directly related to the standard deviation of the wind elevation angle at the point of release. Turner (19) stated that Cramer derived a formula which incorporated the standard deviations of the Gaussian distributions of particle concentrations in both the horizontal and vertical dimensions as coefficients of diffusion. Turner (19) further stated that Hay and Pasquill established a method for deriving the spread of pollutants from records of wind fluctuation. Pasquill (21) subsequently proposed another model to use when wind fluctuation data are not available. It involved utilizing empirically derived curves for diffusion coefficients based on angular spread values in the horizontal and vertical dimensions as a function of distance down-

wind in several categorized atmospheric stability conditions. Gifford (22) followed by converting Pasquill's values of angular spread into standard deviations in the vertical and horizontal directions to fit the Gaussian distribution of plume spread. In spite of the fact that there was a great demand for an equation that was readily amenable to field situations one was not made available until Turner (19) proposed an equation based on Gifford's conversion factors and Pasquill's model to produce a simplified equation. Turner's formula fits into a three dimensional coordinate system which is illustrated in Figure 1. Figure 1 also shows the Gaussian distribution of plume spread with the incorporated diffusion coefficients expressed as standard deviations. In summary, the equation utilizes a statistical approach whereby coefficients of diffusion are incorporated as standard deviations of the Gaussian distributions of particle concentrations in both the horizontal and vertical dimensions. It involves utilizing empirically derived relationships for diffusion coefficients (standard deviations) based on angular spread values in the horizontal and vertical directions as a function of distance downwind in several categorized atmospheric stability classes. The basic equation proposed is:

$$X_{(x,y,z)} = \frac{Q}{u\,\Pi\,\sigma_y\,\sigma_z} \exp\left[-1/2\left(\frac{y^2}{\sigma_y{}^2} + \frac{H^2}{\sigma_z{}^2}\right)\right]$$

X = Concentration downwind (mppcf).

(x,y,z) = Coordinate points.

Q = Emissions Rate (mppcf/second).

u = Windspeed (fps).

H = Effective height of emission (ft).

Π = 3.1416

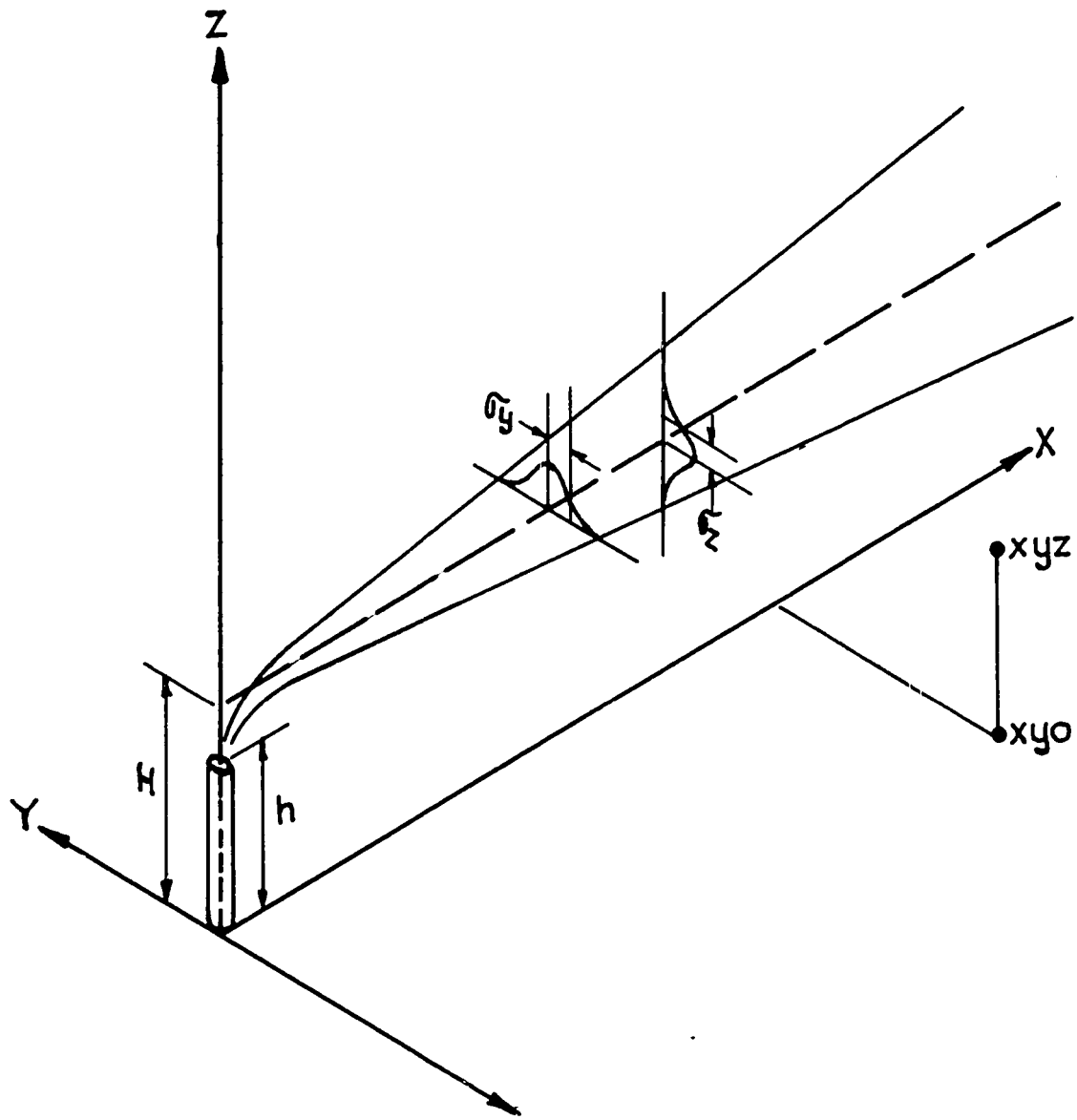


Figure 1. Coordinate system showing Gaussian distribution of plume spread.

σ_y = Standard deviation in the crosswind direction of the plume concentration distribution (ft).

σ_z = Standard deviation in the vertical direction of the plume concentration distribution (ft).

Turner (19) further states that for ground level concentrations with no effective stack height (H) and the source of emissions at ground level, the equation (as it would apply to an activated sludge unit) simplifies to:

$$X(x,y,o) = \frac{Q}{\pi \sigma_y \sigma_z u} \exp\left[-1/2 \left(\frac{Y}{\sigma_y}\right)^2\right]$$

This equation fits into the three dimensional coordinate system as is illustrated in Figure 2 which shows the coordinate system superimposed over the aeration gallery of the activated sludge unit.

To this point in time, a dispersion model had not been applied to the activated sludge unit, therefore emission rates had not been determined. The studies that have been conducted have been limited to bacterial concentrations downwind from the sludge unit, and no information has been gathered relating to overall particulate emissions. It was imperative that emission rates be calculated and particulate distributions evaluated in order to determine the significance of the activated sludge unit as an air pollution source.

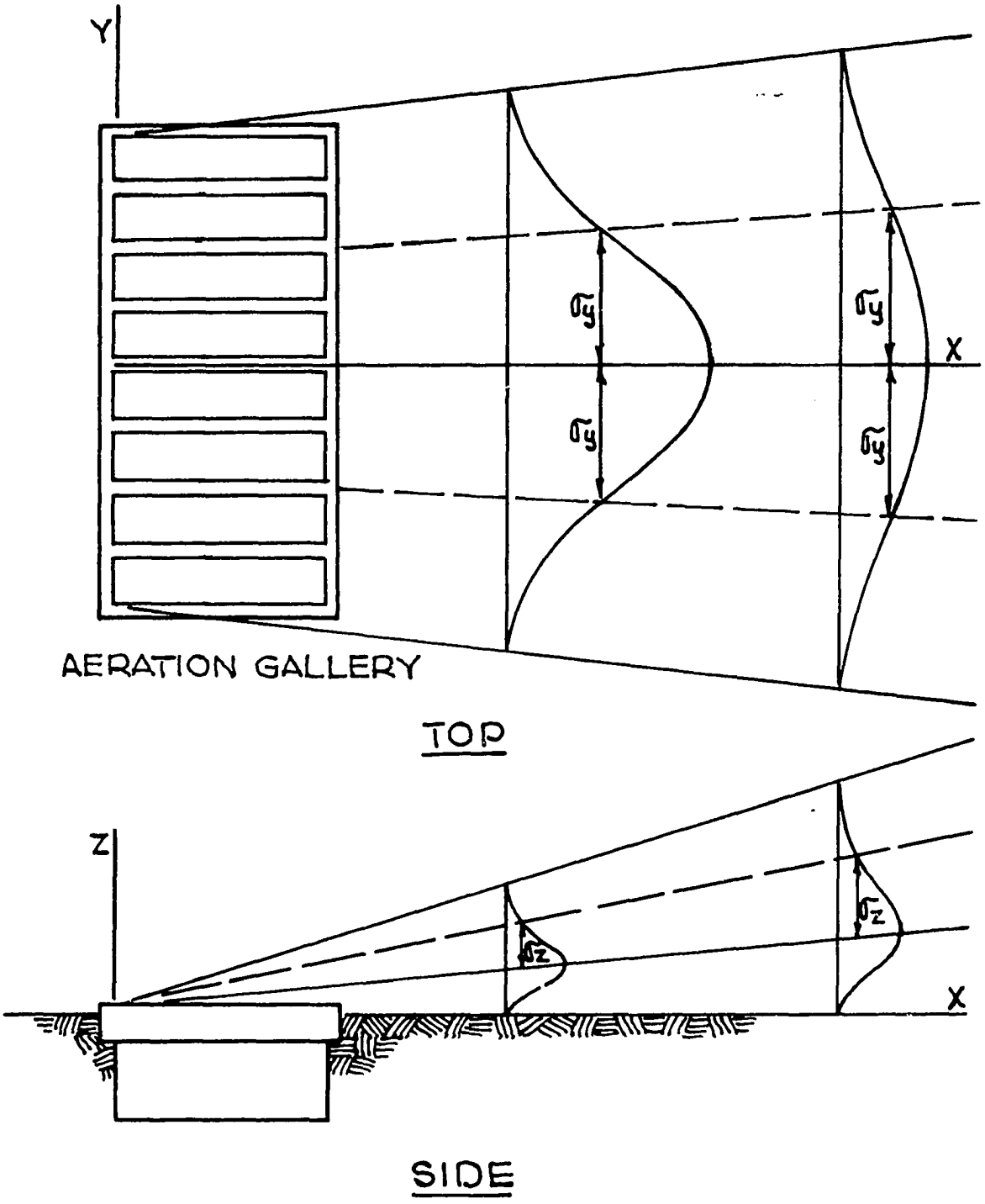


Figure 2. Three-dimensional coordinate system and Gaussian distribution of plume spread as it applies to the activated sludge unit.

CHAPTER III

PURPOSE AND SCOPE

It can be projected that the use of activated sludge units for sewage treatment will increase in the years ahead as they are suitable for treating large volumes of urban sewage and the present demographic trends are toward increased urban growth.

The activated sludge unit in the past had been investigated as an air pollution source in respect to bacterial emissions. The scope of past investigations has been limited to collection and identification of bacteria short distances downwind from the treatment units. The purpose of this study was to further evaluate the sludge unit as an air pollution source by means of describing and evaluating the atmospheric dispersal mechanism associated with the emissions of particulates from the activated sludge unit. Specifically, the dispersal mechanism was to be evaluated with respect to distance and concentration of particulates at increased distances from the unit, and emission rates were to be determined mathematically using Turner's dispersion formula by incorporating observed meteorological parameters of dispersion and observed contaminant concentrations downwind. A size-count distribution and determination of concentration and overall protein content of particulate emissions were to be undertaken to further determine the significance of the activated sludge unit as a primary air pollution source.

CHAPTER IV

MATERIALS AND METHODS

The Northside Water Pollution Control Plant, a conventional activated sludge process located in the Lincoln Park area north of the zoo in northeastern Oklahoma City, was selected as the site for this investigation (Figure 3). During the course of the investigation the plant was enclosed in a fenced area 495 ft wide by 1309 ft long and was contained in a tree-fringed man-made crater which encompassed the functional areas of the plant. The plant was treating domestic sewage from the Deep Fork Relief Sanitary Sewer at a mean rate of 10.8 mgd.

The aeration area consisted of a gallery of eight aeration tanks, with each having an operational capacity of 473,500 gal. The retention time in the interconnected tanks averaged 4.8 hours, with a 33.3 per cent recycling of sludge. Air injection averaged 12 million ft^3 of air per day which provided both oxygenation and agitation of the mixed liquor.

Secondary sedimentation of the effluent from the aeration tanks was accomplished by four clarifiers before the final effluent was discharged into Deep Fork Creek. Waste sludge from the aeration tanks and raw sludge from the primary settling tanks were pumped to two primary digesters backed by two secondary digesters. The digested sludge was

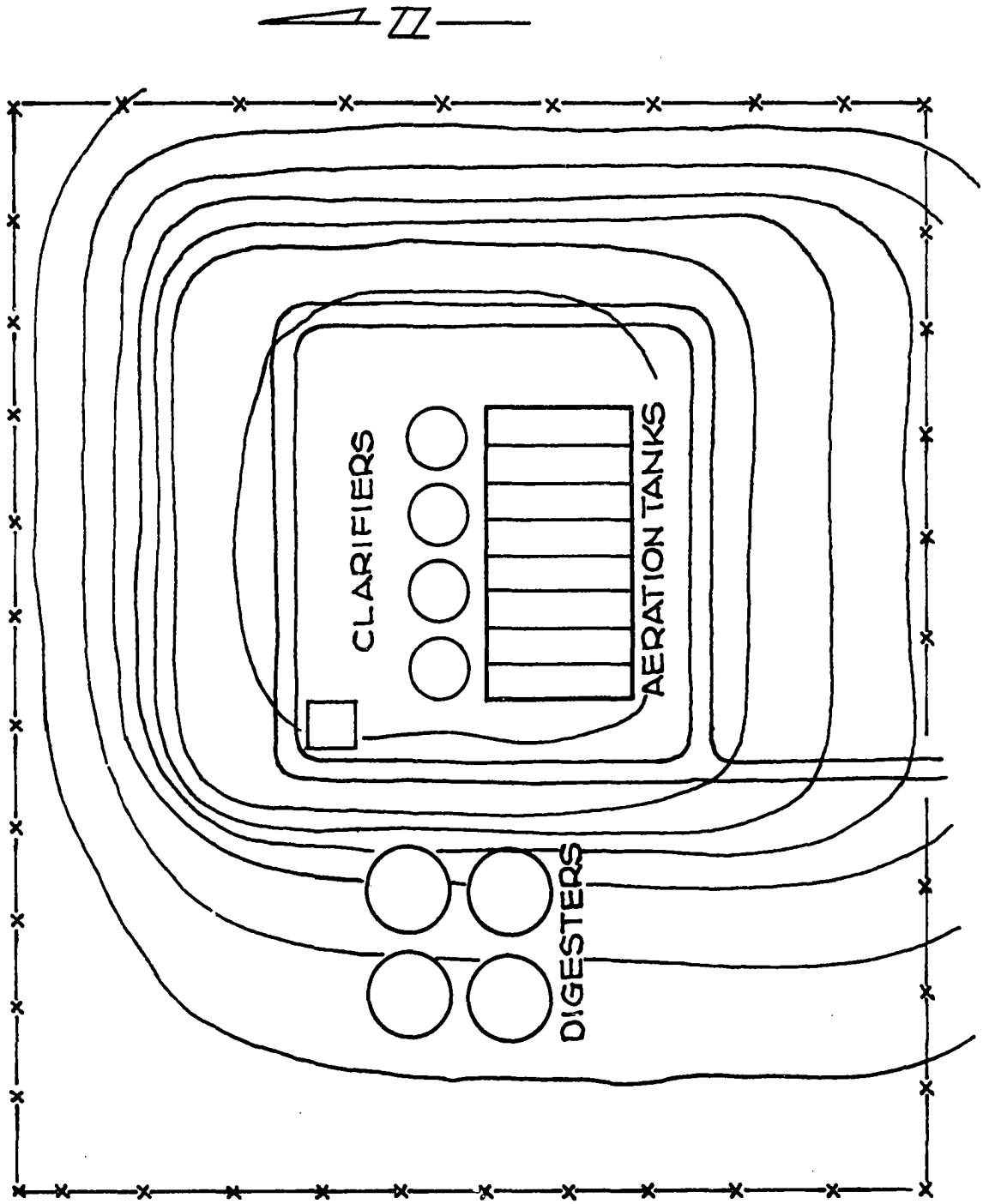


Figure 3. Layout of Oklahoma Northside Sewage Plant with topographical relief.

pumped to drying beds and the drainage from the drying beds was recycled into the plant system.

Concurrent with the study period, an attempt was being made to increase the plant's sewage treatment capacity. Floating electrically-driven Gelman mechanical surface aerators were being placed at different locations in the tanks in order to establish the most functional application of these units in conjunction with the compressed air routinely utilized in the plant. It was estimated that 12 floating aerators would increase the plant capacity by 150 per cent of its previous capability.

Because of a predominant south wind, and the structural features of the plant, a site to the north of the aeration tanks was selected as the sampling area. Since a central reference point of origin was more amenable to graphic representation, a projected phantom point source, south of the aeration tanks, was used instead of a line source of origin. From the point source the sampling area was confined within a 21° angle which extended through the northern edges of the aeration gallery. The sampling area was gridded by extending concentric arcs, spaced 20 ft apart, from the north side of the aeration gallery to the plant fence. In addition, radial lines intersecting the arcs were used to divide the sampling area into 20-ft square grid units. Sampling points were located at the corners of the grid units, and were marked by orange colored wooden stakes. The arcs were labeled alphabetically beginning at the first arc north of the aeration gallery and the radial lines were labeled numerically beginning at the left side of the sampling area thus each grid point had a coded number for easy distinction (Figure 4).

During each sampling period meteorological information was col-

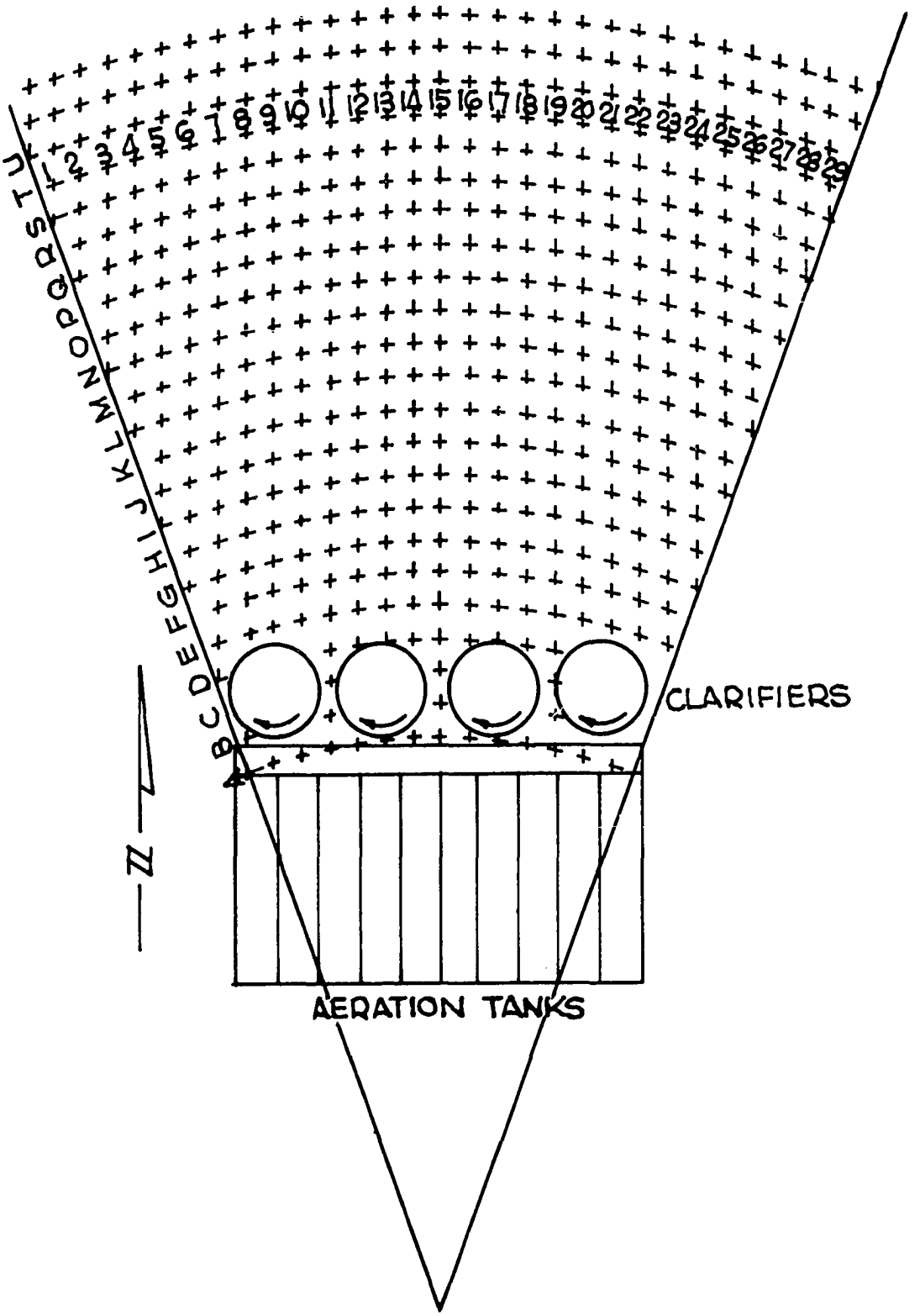


Figure 4. Sampling area and grid system adjacent to the aeration gallery.

lected. Cloud cover information was determined visually by the method described by Turner (19). Other information pertinent to atmospheric stability and dispersion was collected instrumentally. Temperature and relative humidity were obtained utilizing a Sufft hygrometer, windspeed and wind direction were recorded by a Wong EcoWind 111 wind measuring system, and the barometric pressure was determined by using an Airguide marine barometer. All of the instruments were calibrated by the methods recommended by the manufacturers. All the meteorological data were obtained within the gridded area of the plant and at the time of sampling. This information was used for establishing atmospheric stability classes and dispersion patterns at the plant site.

Before sampling could take place certain meteorological criteria had to be met. Because the sampling grid system was to the north of the plant, sampling could not take place unless the wind was out of the south, and more specifically it had to be confined within the range of south-southwest to south-southeast to insure that the windline traversed the sampling grid system. During periods of rain particles are selectively washed from the atmosphere, therefore sampling did not take place since a representative particulate air sample was impossible to collect. When sampling was allowed each sampling period was confined to a 1-hour period.

During the first 20 1-hour sampling periods, three air samples were taken per sampling period. One sample, designated as the control, was taken up-wind from the aeration gallery and was presumed to be representative of the normal ambient air loading of particulates. Another sample, designated as the "wind sample", was located downwind from the

gallery on the grid point nearest the direction of the predominating wind. The other sample, designated the "random number sample", was located on the same arc of the grid by a table of random numbers of sufficient size to include all possible sampling points on that arc. Upon evaluating data at the mid-point of the investigation it was decided that an additional downwind sample would be needed to get a more accurate estimate of the dispersion patterns. Therefore the subsequent 21 sampling period had three downwind samples. The wind selected sample was still utilized, however the method of selecting the downwind random sampling points was changed. Each random sample was to be equal distance from the center line wind sample. Therefore, distance was selected on the basis of the table of random numbers and the grid points closest to the random number distances were selected. After each sampling period each sample was labeled according to date, time and grid point number.

All the particulate air samples were taken on Millipore cellulose acetate membrane filters with a pore size of 0.45 microns. Two of the downwind sampling devices were Gelman sequential air samplers. The other downwind sampler was a Research Appliance Company sequential air sampler. The control sampler consisted of a Gelman vacuum-pressure pump with an attached millipore filter holder. All of the air samplers used were calibrated for air flow with a Precision Wet Test Meter. The flow rates in the field were controlled by the calibrated rotometers of the sampling units. Each sampling period was 1-hour long and the volume of air sampled in that 1-hour period was 10 ft^3.

After each sample was taken it was stored in a covered Millipore plastic petri dish and subsequently stained for protein as described by

Magill and Lumpkins (23). Ninhydrin is frequently used to stain proteinaceous matter as it reacts with amino groups and produces a blue color, but the color is not sufficiently intense to distinguish small particles under the microscope. By treating protein-bearing particles first with nitric acid followed by ninhydrin and a second stain of Wool Fast Pink RL an intense reddish pink color is developed in the protein particulates. The color is clearly apparent, in 5-micron diameter particles and is revealed in particles as small as 1 micron.

The reagents used were as follows:

A. 1 per cent by weight aqueous nitric acid.

B. 1 per cent aqueous solution ninhydrin in water.

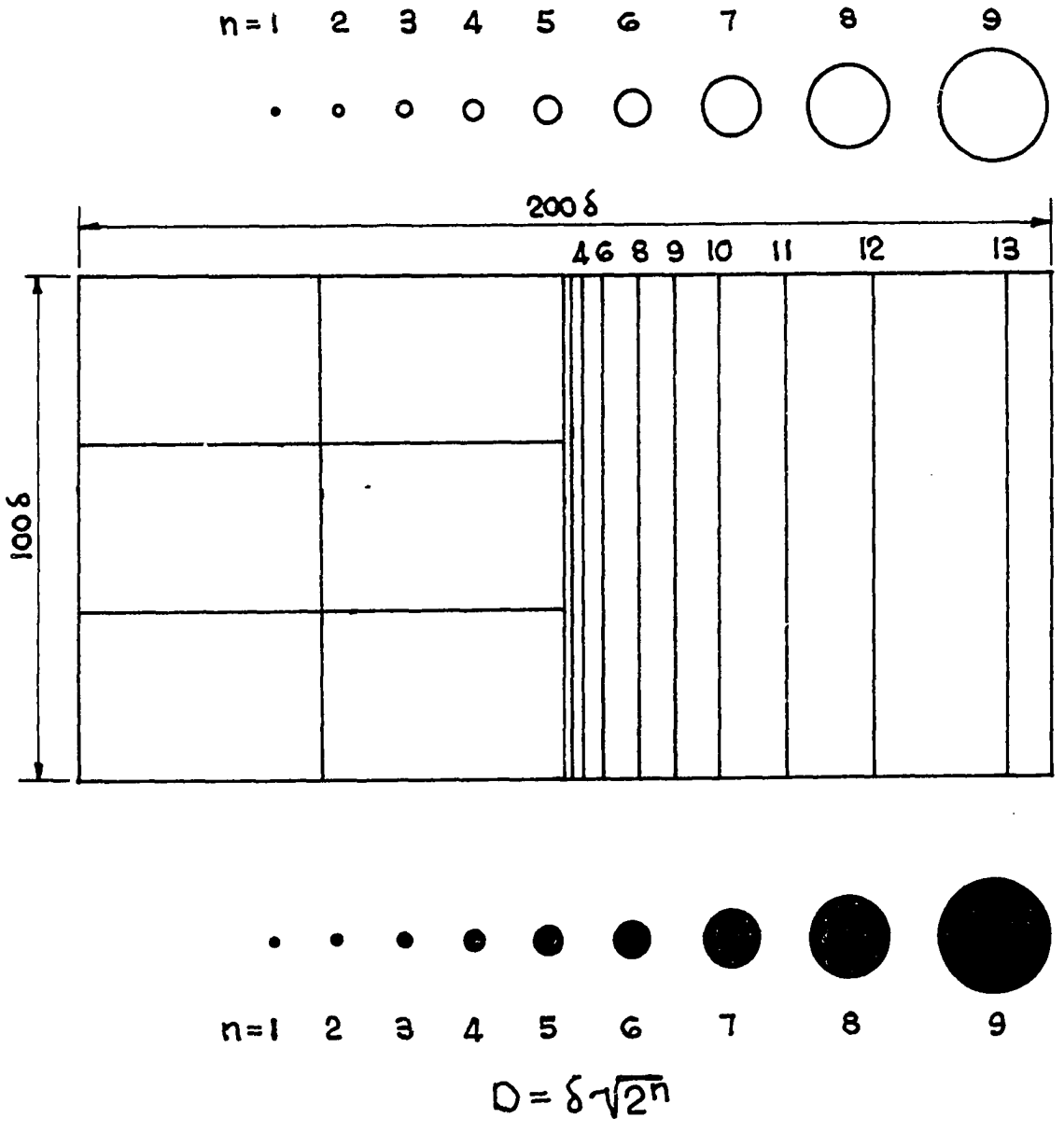
C. 0.2 per cent Wool Fast Pink RL in 10 per cent acetic acid solution.

D. 95 per cent undenatured ethyl alcohol.

The procedure followed was to place in each of four large petri dishes, an adsorbent paper pad the same diameter as the Millipore filters. To each of the petri dishes just sufficient amounts of reagent A, B, C, and D were added to saturate the individual pads without immersing them. Subsequently the Millipore filters, with particle deposition side up, were individually placed on adsorbent Pad A (nitric acid for 2 minutes), Pad B (ninhydrin for 2 minutes), Pad C (Pink RL for 2 minutes), and Pad D (ethyl alcohol for 2 minutes). The bottom side of the filter was blotted on a paper towel after each treatment to remove excess solution. Following the final treatment the filter was dried for 15 to 20 minutes at room temperature in a covered petri dish. The dried filter was then placed on a microscope slide and made transparent with immersion oil for

final microscopic examination. Special care was taken not to use excess oil in mounting the filters in order to eliminate particle displacement on the filter. Permanent slides were made by sealing the cover slip to the slide with clear fingernail polish.

Once the samples were stained and mounted they were examined microscopically utilizing light field techniques. Each sample was analyzed for size-count distribution and particle concentration. Size-counting was accomplished with a Porton graticule (Figure 5) by randomly selecting counting areas on the mounted filter. This eyepiece graticule consists of a glass plate which is placed in the focal plane of the ocular of the microscope. The graticule has two series of circles of various sizes bordering the counting field which are used to determine comparative sizes of the particles being viewed. The circles are on a logarithmic scale numbered from 1 through 9 and the diameter of each circle is defined in arbitrary units by the equation $D = \delta\sqrt{2^n}$ where n represents the number of the circle. The logarithmic scale shows the value of n for the measurement of particles larger than the number 9 circle. Bordering the series of circles is a large rectangle, that includes the counting field, which is 100 δ units in width and 200 δ units in length. Calibration of the reticle was accomplished with a stage micrometer, by determining the dimensions of the retangle in microns, and thus the corresponding circle diameters were calculated. The smallest unit of measure on the graticule was 0.49 microns at 970 X magnification and at 400 X magnification the smallest circle size corresponded to 1.17-microns in diameter. Size-counting was accomplished for both the total amount of particles on the filter and for only protein-bearing particles. The



EXAMPLE:
If $100\delta = 100\mu$
$\delta = 1\mu$

Then $D_1 = 1\sqrt{2^1} = 1.4\mu$
$D_2 = 1\sqrt{2^2} = 2\mu$
$D_3 = 1\sqrt{2^3} = 2.8\mu$
$D_4 = 1\sqrt{2^4} = 4\mu$
Etc.

Figure 5. Porton graticule used for size-counting.

large counting field provided at 400 X magnification was used in counting protein particles as there were sufficient numbers of particles in the large field to provide an accurate representation of the particle distribution. Total counts involved viewing great numbers of particles in the micron and submicron range, therefore the total counts were made at 970 X magnification.

The technique used in making the size-counts was a statistical method of selecting and counting fields in a stratified manner, i.e., representative sampling. The system has been described by Sichel (24) as "Truncated Multiple Traversing". This method was chosen over conventional counting techniques as it improves reliability, minimizes the number of measurements and is more statistically unbiased. The method is based on probability and the basic criterion is that at least ten particles should be observed in any size range which, when combined with the other measurements, has a significant influence on overall curve shape when the distribution is plotted on normalized log paper. For reasons of insured reliability the number of particles observed in each size range in this experiment was 20 particles as opposed to the 10 particles proposed by Sichel (24). The system is best explained by referring to the data in Table 1. In the horizontal row designated as Traverse 1 it can be seen that based upon the criterion of 20 or more particles per size category, sufficient measurements have already been made for Porton sizes 1 through 3. In each Traverse 10 fields are counted. At this point another Traverse of 10 fields is counted, however, this time the measurements are only made for sizes greater than Porton size 3. This is continued until 10 Traverses have been made.

TABLE 1

TRUNCATED MULTIPLE TRAVERSING SYSTEM OF SIZE-COUNTING

Traverse Number	Porton Circle Size									
	1	2	3	4	5	6	7	8	9	≥ 9
1	360[a]	84	29	9	6	2	2	0	0	0
2				10	5	3	2	1	0	0
3				8	6	3	1	0	1	0
4					7	4	2	0	0	0
5						3	1	0	0	1
6						2	1	0	1	0
7						1	0	1	0	0
8						3	2	0	0	0
9							1	1	0	0
10							2	0	0	0
Total	360	84	29	27	24	21	14	3	2	1
Total/T[b]	360	84	29	9	6	2.6	1.4	0.3	0.2	0.1
Cumulated Sum	360	444	473	482	488	490.6	492	492.3	492.5	493.6
Cumulated Per Cent	73.1	90.1	96.0	97.8	99.1	99.6	99.87	99.3	99.97	

[a]Once 20 or more particles were counted in a given size category, that size ceased to be counted.

[b]T = Traverse number and each traverse was comprised of 10 counting fields.

Once all measurements have been made and tabulated each row is totaled and then divided by the Traverse number for the average number of particles per Traverse. These totals are then cumulated and converted to cumulative percentage for each size category. At this point the cumulated percentage was plotted against particle size on normalized log paper, and from this plot the median particle diameter (M_p) and the geometric standard deviation (σ_p) of the given distribution was determined.

In determining the concentration of particles for each sample the grand total of the particles counted using the Traversing system was divided by 10 to get the average number of particles per field as each Traverse was equal to 10 fields. The concentration of particles per ft^3 of air was calculated using the following formula:

$$C = \frac{N_p \, P_m}{A_s}$$

C = Concentration (mppcf).

N_p = Number of Porton counting fields per effective filter area.

P_m = Average number of particles per Porton counting field.

A_s = Volume of air sampled (ft^3).

Once the particle concentrations were determined the control concentrations were subtracted from the corresponding downwind concentrations. This difference in concentration was incorporated into the dispersion equation proposed by Turner (19) to determine emissions rates. However, the formula was originally designed for determining downwind concentration (X), therefore the equation was solved for emissions rate (Q):

$$Q = \frac{X \Pi u \sigma_y \sigma_z}{e^{\{-1/2 [\frac{y^2}{\sigma_y^2}]\}}}$$

At this point it is important to note the two most outstanding limitations of this equation since these shortcomings have a direct effect upon the reliability of the calculated emissions rates. The first source of potential error lies inherent in the diffusion coefficients (σ_y and σ_z) which are empirically derived entities. These coefficients in theory are valid for given field situations, but in nature the coefficient of diffusion may differ from that of the standardized atmospheric stability classes due to changes in such variables as terrain roughness, relative humidity, barometric pressure and possibly the nature of the pollutant itself. The second shortcoming of this equation is the time variable. In theory the equation is mathematically sound, but in field situations the formula may be mathematically unstable as related to the time function. It is assumed that plume concentration follows a Gaussian distribution, and in theory this is true over an infinitesimal amount of time, while in the reality of a 1-hour sampling period this may not be the case, therefore a skewed distribution at the time of sampling will give an inaccurate estimate of the emissions rate. It is evident that a better equation is needed, however at the present time this is still the best equation available for field investigations conducted with a limited amount of meteorological equipment.

As stated earlier, the sampling procedure of this experiment was altered at the mid-point of the investigation by taking 3 downwind samples during the second half of the study as opposed to 2 downwind samples during the first half of the investigation. Therefore, the statistical

analyses of the data was done separately on the first and second phases of the investigation to eliminate any potential differences in variability. The selection of the statistical test used was based on the following criteria:

1) There were pairs of observations to be compared.

2) Each of the two observations of a given pair was made under similar conditions.

3) The different pairs were observed under different conditions.

This last condition generally makes the t-test invalid, since this would usually mean the differences observed have different variances. Since the t-test could not be used with utmost validity, a non-parametric statistic known as the Wilcoxon Matched Pair Rank Sign Test was selected as it best meets the above criteria (25).

CHAPTER V

OBSERVATIONS AND DISCUSSION

The fundamental premise of this investigation was that particles were being emitted from the aeration gallery of an activated sludge unit. This was to be determined by comparing upwind particle concentrations, as controls, with downwind particle concentrations. By making this comparison with the Wilcoxon Matched Pair Rank Sign Test (Wilcoxon Test) it was demonstrated that the downwind particle concentrations were higher than the upwind control concentrations. This difference was shown to be significant at the 0.01 level and the average downwind concentration, irrespective of all dependent and independent variables effecting the concentrations, was 0.4299 mppcf higher than the control concentrations as is illustrated in Table 2 of the Appendix. This in itself most definitely demonstrates that the activated sludge unit was a primary source of particulate air pollutants.

To further substantiate the contention that particles were being emitted, the downwind particle distributions were compared to the control particle distributions. The Wilcoxon Test showed, at the 0.01 level, that the Median Particle Diameter (Mp) of the downwind distribution was greater than the upwind distribution. This is demonstrated in Table 3 of the Appendix, and graphically illustrated in Figure 6. The average

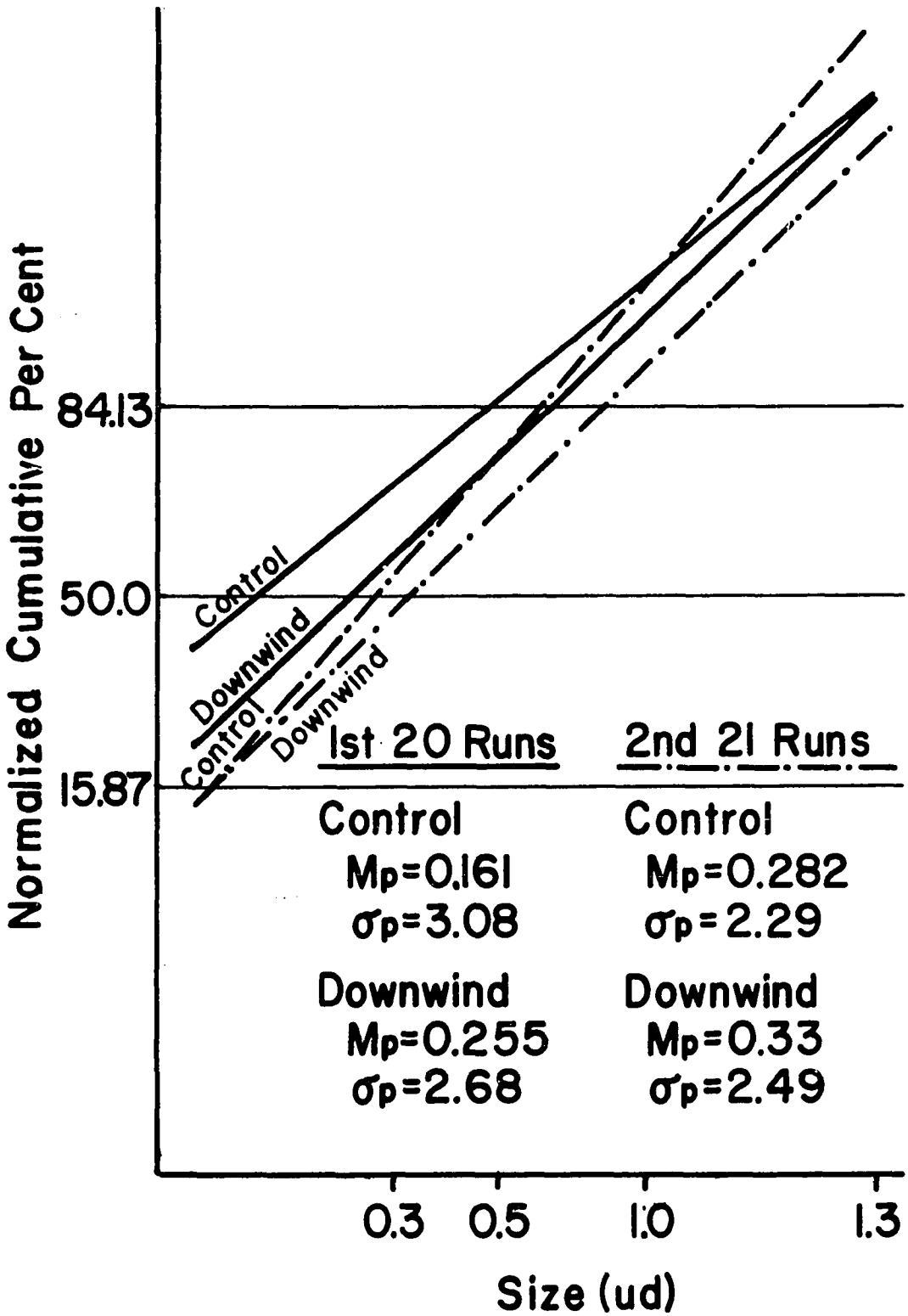


Figure 6. Log-normal distributions of the averaged downwind and control total particle counts.

Mp downwind was 0.293 microns in diameter (μd) as compared to 0.222 μd for the particles upwind. This parameter of the distributions definitely shows that the particles were from different populations and were therefore generated by the activated sludge unit, and those particles that were being generated were of such a size that they could be readily inhaled, and dispersed for great distances.

The other parameter of the particle distributions compared was the Geometric Standard Deviation (σp) or the slope of the particle distributions. The σp is an important parameter to consider since it determines the numbers or percentages of particles in given size ranges when the particle distribution is plotted on log-normal graph paper. The Wilcoxon Test demonstrated that the upwind σp was greater than the downwind σp for the first 20 runs (Figure 6). The statistic demonstrated that for the second 21 runs the downwind σp was greater than the upwind σp (Figure 6). The explanation for the differences in the directions of the σp's for the first 20 runs and the second 21 runs can be accounted for by differing plant operating parameters for the first and second halves of the investigation. During the first half of the experiment fewer mechanical floating aerators were being used than in the second half of the investigation. By applying linear regression and correlation to the number of aerators used and the corresponding σp's it was found that as the number of aerators increased σp also increased. The slope of this increase was 0.085 with each additional aerator and the intercept was -0.71. The correlation coefficient for this relationship was 0.56. One explanation of this increase of σp lies in the fact that as the number of aerators increased the size of the particles decreased,

thus adding greater numbers of small particles to the lower end of the particle distribution. This is shown in Table 4 of the appendix. This further upholds the contention that the downwind particle distributions were different from the upwind distributions and therefore the particles were generated by the activated sludge unit.

During the course of the study it was observed that windspeed was a very important parameter to be considered when evaluating the downwind concentrations. By categorizing the various observed downwind concentrations (minus control concentrations) into four windspeed categories it was evident that as windspeed increased the number of particles in the air downwind dramatically increased until a windspeed of approximately 12 mph was reached. At speeds greater than 12 mph the increase in numbers of particles was at a reduced rate. This is illustrated in Table 5 (Appendix) and in Figure 7. This increase was verified and evaluated by linear regression and correlation. The slope of the increase was found to be 0.048 mppcf with each mile per hour increase in windspeed with intercept at 0.22 mppcf. The correlation coefficient was 0.74, thus a definite relationship exists. The mechanism suspected of causing this increase was the breaking up of the aerosols being generated causing higher numbers. This contention was born out by the fact that as windspeed increased to 12 mph the Mp of the downwind concentrations decreased from 0.276 μd to 0.127 μd and the σp of the distributions showed a decrease which also indicates a possible increase in the numbers of smaller particles being generated. These Mp and σp parameters are shown in Table 6 of the Appendix. Thus windspeed is an important parameter when considering the activated sludge unit as an air pollution source since windspeed

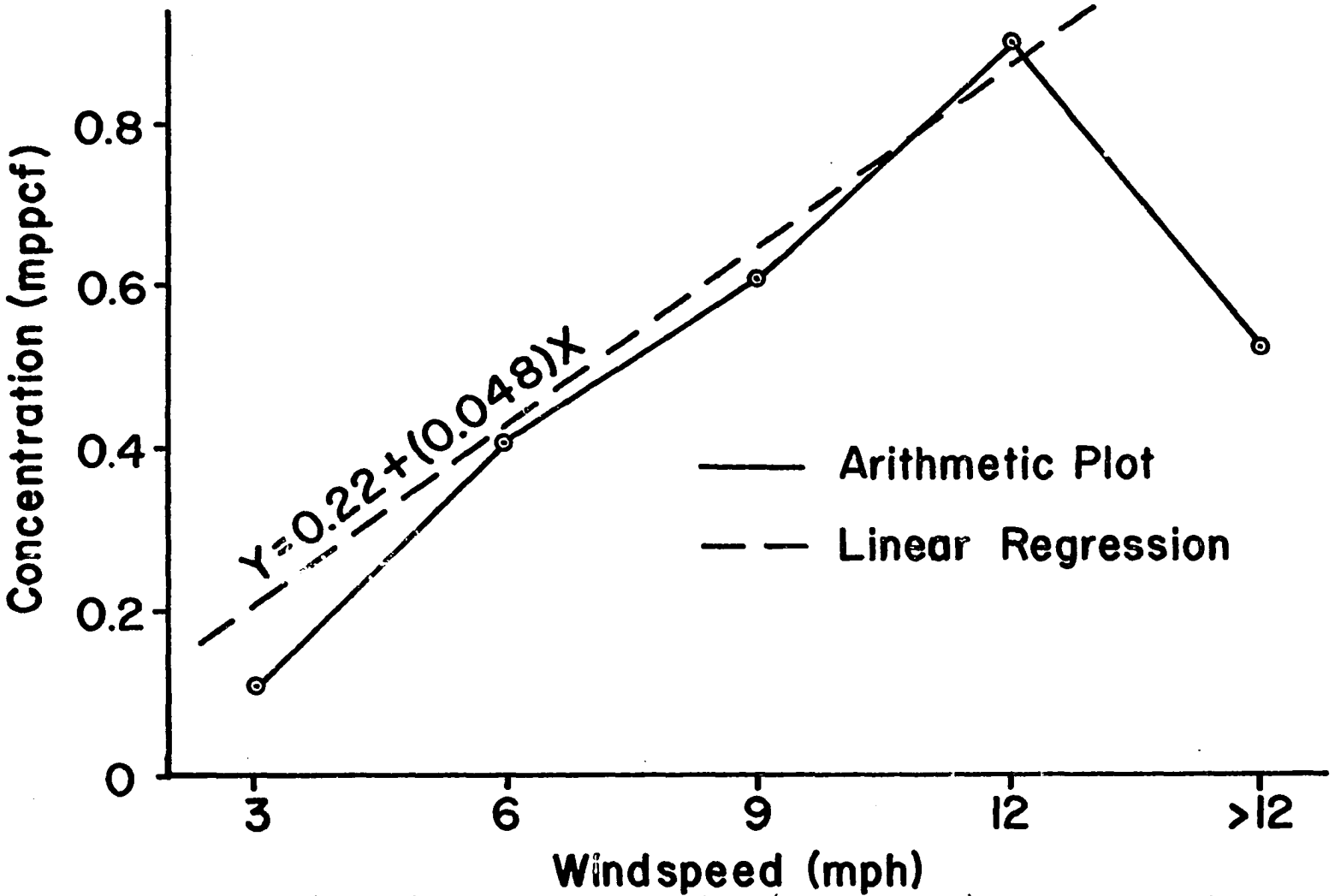


Figure 7. Total downwind particle concentrations (minus control) versus windspeed.

can increase not only the numbers of particles, but also it tends to decrease their size which can have a greater effect on health as the greater numbers of smaller particles can more readily enter the pulmonary system. In addition their smaller size makes them more aerodynamically stable so they can be ied greater distances from the plant site.

Since it was suspected that the particles generated were of such size that they could be carried great distances, thus effecting people living in the vicinity of the activated sludge unit, an attempt was made to determine if the increased downwind concentrations decreased appreciably with increasing distance from the source. The maximum distance at which samples were taken was 200 feet from the aeration gallery. It was not felt that a decrease in concentration would be observed in this short distance, however, a minor decrease in concentration was observed as is illustrated in Figure 8 and in Table 7 of the Appendix. Linear regression revealed that the slope of the line was -0.0004 mppcf with each foot of distance from the plant. The intercept of this line was 0.559 mppcf and the correlation coefficient was 0.28. It should be noted that in the greater distances of the arithmetic plot (Figure 8) there was a definite increase in concentration with increased distance and should samples have been taken at 240 feet a further increase in concentration may have eliminated the negative slope demonstrated by regression analysis. As it stands this was still an insignificant decrease in concentration (-0.0004 mppcf) with increased distance and the correlation was relatively weak, therefore it is postulated that residents in the immediate vicinity of the plant site were in jeopardy of exposure to the particulates emitted.

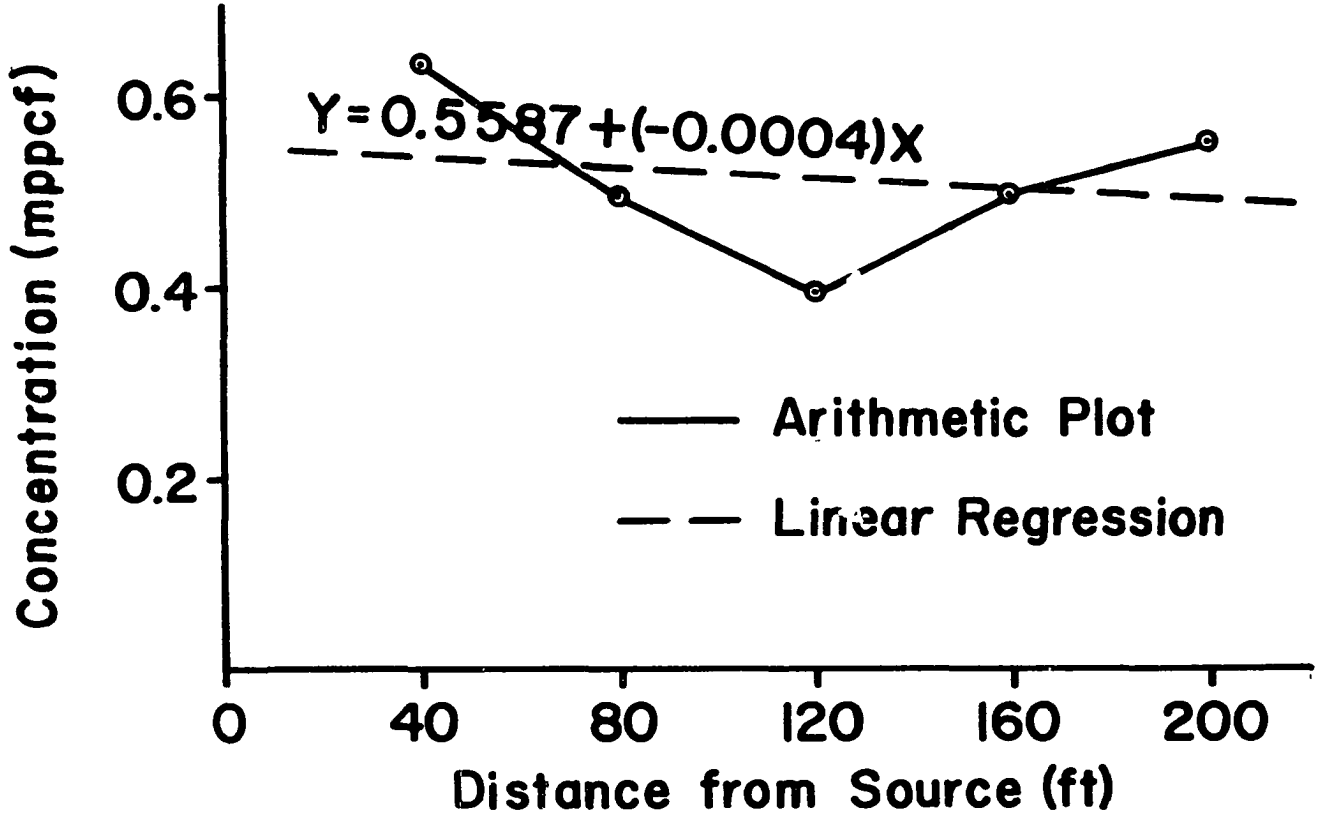


Figure 8. Downwind total particle concentrations (minus control) versus distance.

In order to have a more thorough understanding of the significance of the activated sludge unit as a primary air pollution source of particulates, emissions rates were calculated using Turner's diffusion equation. The rates were expressed as millions of particles per square foot per second (mppsfs). Since there was a wide range in the emissions rates calculated, the rates were averaged to get an overall estimate that could be applied to the activated sludge unit. In Table 8 of the Appendix it can be seen that the standard deviation around the mean emission rate was an order of magnitude higher than the mean rate, thus rendering the mean rate useless as an overall emission rate estimate. It was felt that this tremendous variability was due to an inherent source of error built into the diffusion equation. As was stated in Chapter IV, Turner's diffusion equation is mathematically unstable as it is related to the time function. The equation assumes a Gaussian distribution of plume spread that is only valid over an extremely long period of time. It was felt that by averaging over all the diffusion parameters of the investigation and calculating an emission rate based on these averages the time function error could be dramatically reduced which would give a much better estimate of the emission rate. This would give a rate based on 104 hours of sampling versus the emissions rates calculated on 1-hour sampling periods, therefore allowing the plume spread to better approach the theoretical Gaussian distribution. By using this method the overall estimate of emission rate for total particulates emitted was 3.543 mppsfs. Based on an emission rate of this magnitude it can certainly be stated that the activated sludge unit is a significant source of particulate air pollutants.

Protein Particulates

An important premise of this investigation was that the activated sludge unit was emitting proteinaceous particles. This was to be investigated by comparing upwind protein particle concentrations with downwind proteir particle concentrations and also by comparing the upwind and downwind protein particle distributions (Mp and σp). The statistic used to make these comparisons was the Wilcoxon Test.

In reference to the protein particle concentrations it was demonstrated that the downwind protein particle concentrations were higher than the upwind protein particle concentrations and this was shown at the 0.01 statistical significance level. The overall mean difference in concentration was 9.192 thousand particles per cubic foot (tppcf) of air. This is illustrated in Table 9 of the Appendix.

The overall downwind protein particle Mp was found to be smaller than the Mp of the control and this difference was demonstrated at the 0.01 level with the Wilcoxon Test, specifically the downwind Mp was 2.58 μd as compared to 4.13 μd for the control samples. This relationship is shown in Table 10 of the Appendix and also in Figure 9. The other parameter of the protein particle distributions evaluated was σp and it was found that the σp of the downwind protein particle distribution was greater than the control protein particle distribution. This difference was significant at the 0.01 level and more specifically as is illustrated in Figure 9 and Table 11 of the Appendix, the overall difference in σp's was 0.414 with the control σp equal to 1.94 and the downwind σp equal to 2.35.

These differences in upwind and downwind protein particle con-

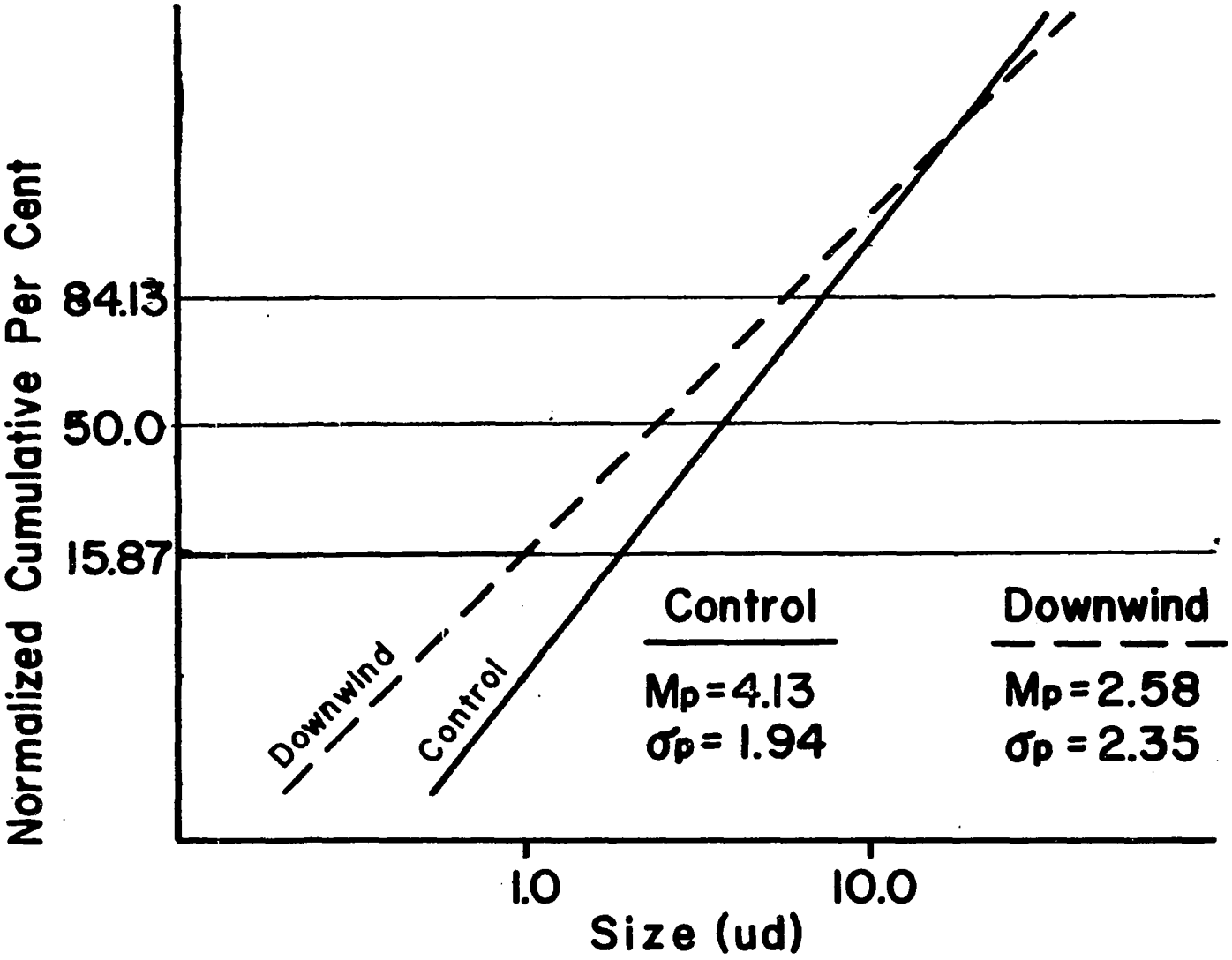


Figure 9. Overall log-normal protein particle distributions for downwind and control samples.

centrations and protein particle distributions definitely support the premise that the activated sludge unit is emitting protein-bearing particulates. In addition to this the protein particles emitted were of smaller size than the background protein particles. The Mp was smaller and the σp was larger which indicates the added numbers of smaller particles were raising the lower portion of the distribution thus increasing the downwind σp. It can be concluded that the activated sludge unit was emitting protein particles that were in the respirable range (i.e., less than 7 μd) and that the particles were of such size that they were aerodynamically stable enough to reach people living in close proximity to the plant site.

As with the total particulate emissions, it was demonstrated that windspeed is an important parameter to consider when evaluating the activated sludge unit as a source of protein particulate emissions. By comparing windspeed to downwind protein particle concentration (minus the control protein concentration) it was observed that as windspeed increased the number of protein particles downwind increased. Using linear regression it was ascertained that this increase was 2.12 tppcf (slope) for each mile per hour increase in windspeed. The intercept was 0.5959 tppcf and the correlation coefficient was 0.40. This is illustrated in Figure 10 and Table 12 of the Appendix. The same explanation used for the observed increased concentration with increased windspeeds of the total emissions is used here. As windspeed increases the aerosols generated were broken up into greater numbers of smaller particles. This contention was supported by the fact that as the windspeed increased the Mp of the downwind protein distributions decreased (Table 13, Appendix).

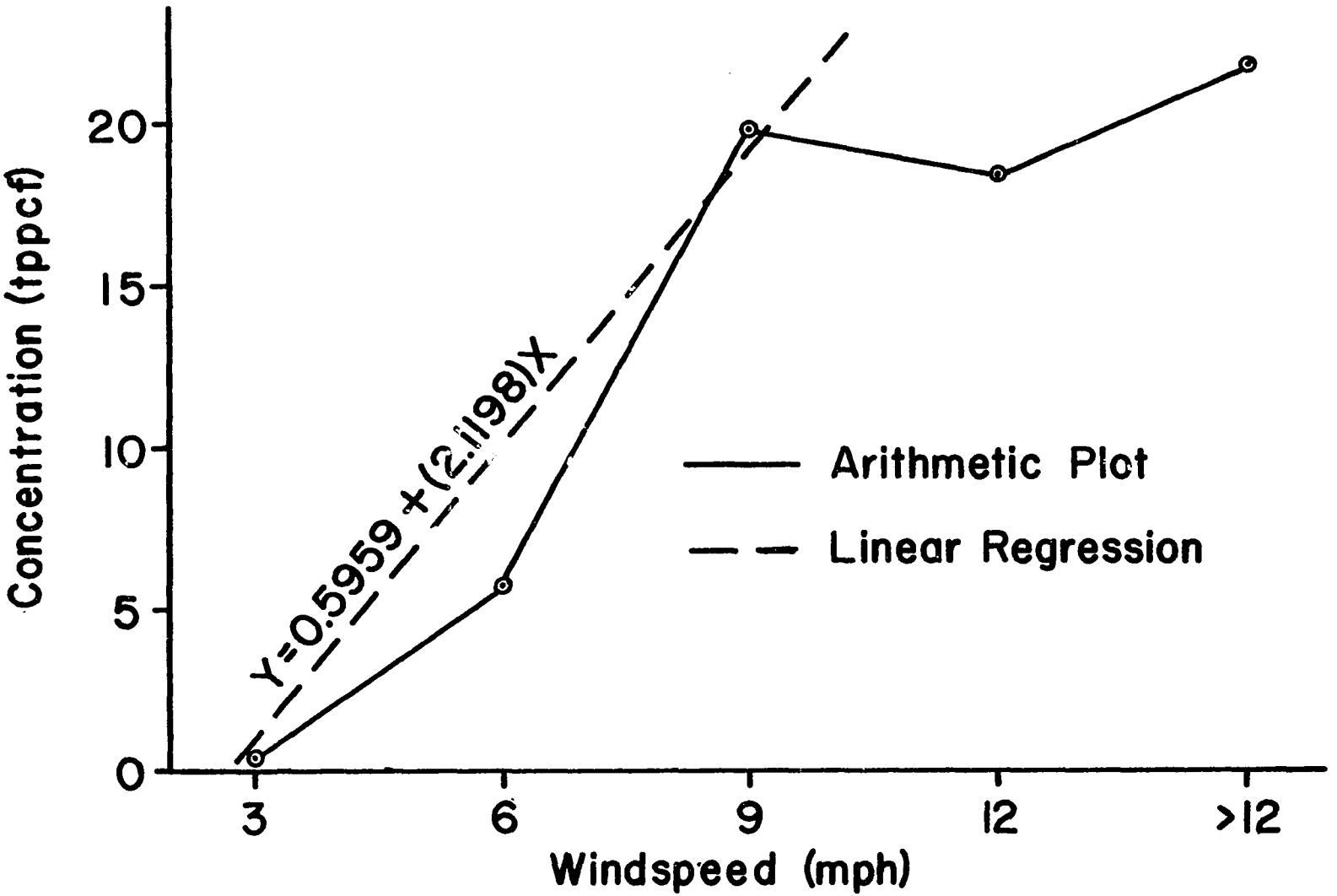


Figure 10. Downwind protein particle concentration versus windspeed.

In addition as windspeed increased the downwind protein σp increased, i.e., more smaller particles in the lower end of the distribution (Table 13, Appendix). Therefore windspeed was important from the standpoint of creating larger numbers of smaller respirable protein particles that could be carried greater distances and potentially effecting greater numbers of people, not only plant employees.

A comparison was made of downwind protein concentration minus the control concentration with increased distances from the source. As is shown in Table 14 of the Appendix and graphically illustrated in Figure 11 there was a very slight decrease in concentration at 200 feet away from the aeration gallery. With linear regression it was observed that the slope of this decrease was -0.0005 tppcf with each increasing foot in distance and the intercept was 10.001 tppcf. The correlation coefficient was -0.009 which indicated no relationship between distance and concentration in this short distance. When this same comparison was made with total particulates a much greater decrease in concentration was observed, but it was still maintained that the decrease was insignificant. The fact that there was no relationship between increased distance and decreased concentration observed with the protein concentrations further supports the premise that there was no significant decrease within 200 feet of the source. Therefore it can be assumed that the total and protein particulates were being carried away from the plant site, thus potentially affecting any residents in the immediate area.

Protein emissions rates were calculated for all the sample runs and averaged for an overall estimate of emission rate, but as with the total emission rates the standard deviation around the mean rate was an

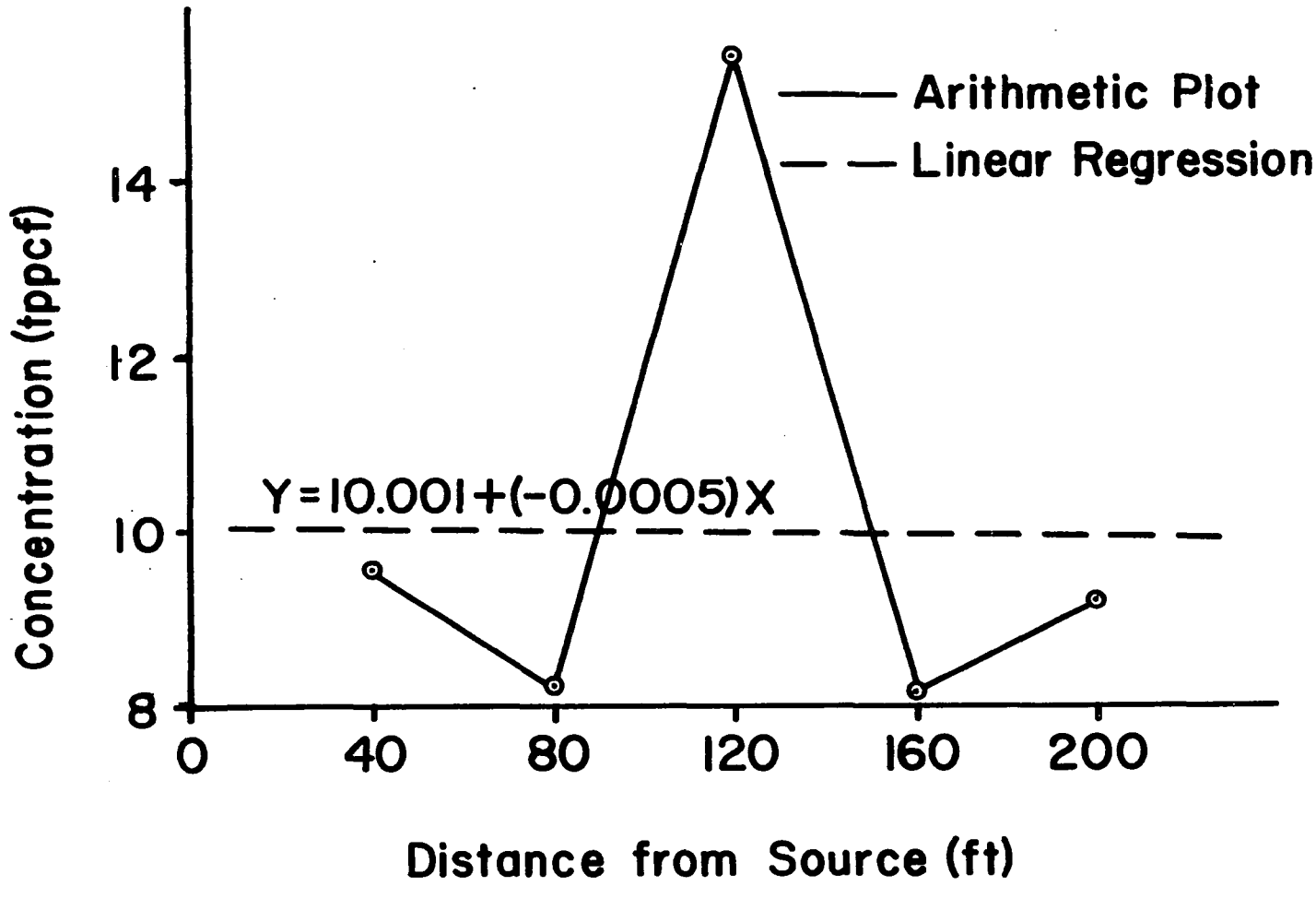


Figure 11. Downwind protein particle concentrations (minus control) versus distance.

order of magnitude higher than the mean, rendering this mean useless as an estimate of overall protein emission rate. Therefore, the diffusion parameters of all the sample runs were averaged and incorporated into the diffusion equation for a more valid estimate of the overall protein particle emission rate. The emission rate that was arrived at was 0.076 mppsfs. This is a large and impressive number of protein particles emitted, thus it can be concluded that this activated sludge unit was a source of air pollution, especially in respect to protein particulate emissions.

CHAPTER VI

SUMMARY AND CONCLUSIONS

This research was undertaken to determine if the activated sludge unit was a primary air pollution source with particulate emissions of possible health significance. This determination was based on emission rates and atmospheric dispersion patterns of particulates downwind from the plant site. Specifically the diffusion mechanism was evaluated with respect to distance and concentration of particulates at increased distances from the plant, and emission rates were determined mathematically using Turner's dispersion equation. This was accomplished for both the total numbers of particles generated and for the protein particles emitted. To ascertain whether particles were being emitted, paired air samples were taken upwind and downwind on membrane filters. Each sample was differentially stained and microscopically size-counted for numbers of total and protein particulates. The paired samples were statistically compared by the Wilcoxon Matched Pair Rank Sign Test for concentration and particle distribution. Subsequent to this, downwind concentrations and distributions were related to windspeed and distance from the source. This investigation revealed that:

1. The activated sludge unit was emitting particles into the air. This was illustrated by fact that the total number of particles

per ft^3 of air downwind from the aeration gallery was higher than the upwind control concentrations.

2. The activated sludge unit was generating particulates that were of proteinaceous composition. The evidence supporting this conclusion was the observation that the concentration of protein particles in the air downwind from the aeration gallery was higher than the concentration upwind from the aeration gallery.

3. The particle distribution downwind from the aeration gallery was different from the upwind distribution and the slope of the downwind distribution was effected by the number of floating mechanical aerators in operation. In all cases the Mp was larger downwind and the σp differed. When few floating aerators were used the downwind σp was less than the upwind σp and when many aerators were used the downwind σp was greater than the upwind σp. In addition the particles generated were in the respirable range.

4. The protein particles generated were of special health significance as they were well within the respirable range. The downwind Mp was smaller than the upwind Mp, i.e., smaller protein particles were being generated by the unit than were found in normal background samples. Supplemental to this the downwind σp was significantly greater than the control σp further supporting the premise that these particles were generated by the activated sludge unit as the particle distributions were from different populations.

5. It was determined that windy days were especially bad in respect to potential health effect and with respect to the particle transport potential. As windspeed increased it was observed that greater

numbers of particles were generated, both protein and nonprotein. Not only were greater numbers of particles emitted, but the particles decreased in size as windspeed increased, therefore the smaller particles could be more readily inhaled and the particles emitted could be carried greater distances, thus effecting a larger population of people.

6. It was ascertained that the particles generated by the activated sludge unit were not confined to the plant site. There was not a significant decrease in total particle or protein particle concentration at a distance of 200 feet downwind from the aeration gallery. Therefore not only were the plant employees in jeopardy, but residents in the immediate area were also being exposed.

7. By using Turner's atmospheric diffusion equation it was determined that great numbers of protein and nonprotein particles were being generated. However it was observed that 1-hour sampling periods were not long enough to calculate emissions rates by using Turner's diffusion equation as the formula is unstable as related to the time function. Estimates of the emission rates for total and protein particulates had to be based on averaging the diffusion parameters of the entire investigation, thus reducing the effect of the time variable.

To further clarify the significance of the activated sludge unit as an air pollution source, several things should be investigated in the future. An epidemiological study could be carried out in respect to respiratory ailments and allergies of those people working in the plant and those living near the plant site to further clarify the significance of the health effects of the emissions from the activated unit. In the past bacterial emissions from the activated sludge unit have been carried

out and this investigation was limited to particulates, future work needs to be done in the area of other biologicals emitted, such as viruses and fungii. A closer look is needed into types of particles emitted, this could be accomplished by using microscopic fine particle techniques. More knowledge is needed in the area of determining how plant operating parameters (strength and nature of sewage, rate of air injection, etc.) effect emissions from the activated sludge unit in order that good control methods may be devised.

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APPENDIX

LIST OF ABBREVIATIONS

fps	Feet per second
σp	Geometric standard deviation
mppcf	Million particles per cubic foot
mppsfs	Million particles per square foot per second
Mp	Median particle diameter
N	Number of observations
P	Statistical significance level
Q	Emission rate
r	Correlation coefficient
S	Standard deviation
tppcf	Thousand particles per cubic foot
T	Wilcoxon T
μd	Microns in diameter
$\bar{X}$	Mean
$\bar{X}d$	Mean difference
Z	Z statistic

TABLE 2

COMPARISON OF TOTAL PARTICLE CONCENTRATIONS FOR DOWNWIND AND CONTROL SAMPLES

	1st 20 Runs		2nd 21 Runs		Overall
	Downwind	Control	Downwind	Control	
$\bar{X}$	1.752819	1.159674	1.79771	1.553572	-
S	0.335760	0.197358	0.417102	0.238905	-
$\bar{X}d$	0.570703		0.244399		0.429889
Wilcoxon Test					
T	0.0000		0.0000		-
N	20		21		-
Z	3.9199		4.0145		-
P	0.01		0.01		-

$\bar{X}$ = Mean concentration (mppcf)

S = Standard deviation

$\bar{X}d$ = Mean difference

T = Wilcoxon T

N = Number of observations

Z = Z statistic

P = Statistical significance level

TABLE 3

COMPARISON OF Mp FOR TOTAL PARTICLES OF DOWNWIND AND CONTROL SAMPLES

	1st 20 Runs		2nd 21 Runs		Overall	
	Downwind	Control	Downwind	Control	Downwind	Control
Mp						
$\bar{X}$	0.255	0.161	0.330	0.282	0.293	0.222
S	0.056	0.057	0.040	0.050	0.048	0.053
$\bar{X}d$	0.094		0.048		0.071	
Wilcoxon Test						
T	20.0		0.0000		-	
N	20.0		21.0		-	
Z	3.1732		4.0145		-	
P	0.01		0.01		-	

Mp = Median Particle Diameter (μd)

TABLE 4

REGRESSION ANALYSIS FOR NUMBER OF AERATORS VERSUS
GEOMETRIC STANDARD DEVIATION AND
MEDIAN PARTICLE DIAMETER

	Slope	Intercept	r
σp	0.085	-0.71	0.56
Mp (μd)	-0.008	0.112	-0.19

Where:

X axis = Number of aerators

Y axis = Geometric Standard Deviation (σp) or
Median Particle Diameter (Mp)

r = Correlation coefficient

TABLE 5

COMPARISON OF TOTAL CONCENTRATION[a] OF PARTICULATES VERSUS WINDSPEED

Windspeed (mph)		0-3	3-6	6-9	9-12	> 12
Concentration mppcf						
	$\bar{X}$	0.12098	0.41553	0.61369	0.87679	0.57786
	S	0.014	0.141	0.274	0.355	0.201
	N	9	54	20	9	8

[a]Concentration = Downwind concentration minus control concentration.

TABLE 6

COMPARISON OF GEOMETRIC STANDARD DEVIATION AND MEDIAN PARTICLE DIAMETER OF TOTAL PARTICLE DISTRIBUTION VERSUS WINDSPEED

Windspeed mph	0-4		4-8		8-12		> 12	
	Mp	σp	Mp	σp	Mp	σp	Mp	σp
Control								
$\bar{X}$	.276	2.34	.215	2.73	.127	3.07	.232	2.87
S	.060	0.50	.072	0.45	.050	0.32	.050	0.54
Downwind								
$\bar{X}$	.322	2.46	.304	2.61	0.290	2.41	0.179	3.02
S	0.049	0.36	0.062	0.29	0.070	0.45	0.065	0.41

TABLE 7

COMPARISON OF THE TOTAL DOWNWIND PARTICLE CONCENTRATIONS[a] WITH DISTANCE

Distance (ft)	40	80	120	160	200
Concentration mppcf					
$\bar{X}$	0.62838	0.49108	0.39864	0.49915	0.54828
S	0.411	0.313	0.187	0.326	0.199

Linear Regression and Correlation Coefficient (r)

Slope =-0.0004

Intercept = 0.55874

r =-0.28

[a]Concentration = Downwind concentration minus control concentration.

TABLE 8

THE CALCULATED EMISSION RATES FOR TOTAL PARTICLE EMISSIONS AND PROTEIN PARTICLE EMISSIONS

	Total	Protein
Emission Rate (mppsfs)[a]		
$\bar{X}$	1.35249×10^4	1.17046×10^3
S	1.28889×10^5	1.07073×10^4

[a]mppsfs = millions at particles per square foot per second.

TABLE 9

COMPARISON OF PROTEIN PARTICULATES FOR DOWNWIND AND CONTROL SAMPLES

	1st 20 Runs		2nd 21 Runs		Overall
	Downwind	Control	Downwind	Control	
$\bar{X}$	41.196	18.805	11.096	9.034	-
S	27.351	17.603	7.361	5.375	-
$\bar{X}d$	23.152		2.062		9.192
Wilcoxon Test					
T	20.0		0.0000		-
N	20.0		21.0		-
Z	3.1732		4.0145		-
P	0.01		0.01		-

$\bar{X}$ = Mean concentration in thousand particles per cubic foot (tppcf).

TABLE 10

COMPARISON OF Mp FOR PROTEIN PARTICLES OF DOWNWIND AND CONTROL SAMPLES

		1st 20 Runs		2nd 21 Runs		Overall	
		Downwind	Control	Downwind	Control	Downwind	Control
Mp							
	$\bar{X}$	1.59	3.44	3.56	4.82	2.58	4.13
	S	0.45	1.12	1.30	1.07	0.88	1.09
	$\bar{X}d$	-1.85		-1.26		-1.55	
Wilcoxon Test							
	T	0.0000		0.0000		-	
	N	20		21		-	
	Z	3.9199		4.0145		-	
	P	0.01		0.01		-	

Mp = Median Particle Diameter (μd)

TABLE 11

COMPARISON OF THE PROTEIN PARTICLE GEOMETRIC STANDARD DEVIATIONS OF THE DOWNWIND AND CONTROL SAMPLES

	1st 20 Runs		2nd 21 Runs		Overall	
	Downwind	Control	Downwind	Control	Downwind	Control
σp						
$\bar{X}$	2.54	2.17	2.35	1.94	2.45	2.05
S	0.33	0.17	0.17	0.11	0.21	0.14
$\bar{X}d$	0.37		0.414		0.40	
Wilcoxon Test						
T	20.0		0.0000		-	
N	20		21		-	
Z	3.1732		4.0145		-	
P	0.01		0.01		-	

σp = Geometric Standard Deviation

TABLE 12

COMPARISON OF PROTEIN PARTICLE CONCENTRATION VERSUS WINDSPEED

Windspeed (mph)	0-3	3-6	6-9	9-12	> 12
$\bar{X}$	0.2726	5.6098	19.7463	18.1987	22.0513
S	0.162	10.678	23.7600	19.7801	14.6821
N	9	54	18	10	8

$\bar{X}$ = Mean downwind concentration minus control concentration in thousand particles per cubic foot (tppcf).

TABLE 13

COMPARISON OF MEDIAN PARTICLE DIAMETER AND GEOMETRIC STANDARD DEVIATION OF THE PROTEIN PARTICLE DISTRIBUTIONS VERSUS WINDSPEED

Windspeed (mph)	0-4		4-8		8-12		> 12	
	Mp	σp	Mp	σp	Mp	σp	Mp	σp
Control								
$\bar{X}$	4.77	1.95	3.99	2.15	3.84	2.12	3.33	2.20
S	1.41	0.15	1.12	0.29	0.84	0.22	1.61	0.08
Downwind								
$\bar{X}$	3.96	2.30	2.41	2.48	1.77	2.48	1.48	2.43
S	1.42	0.30	1.09	0.35	0.50	0.31	0.29	0.13

TABLE 14

MEAN AND STANDARD DEVIATION OF THE PROTEIN DOWNWIND PARTICLE CONCENTRATIONS MINUS THE CONTROL CONCENTRATIONS VERSUS DISTANCE

Distance (ft)	40	80	120	160	200
$\bar{X}$	9.6794	8.2507	15.4715	8.1880	9.1098
S	1.4581	4.9989	9.2163	4.6197	2.1162

Linear Regression and Correlation Coefficient (r)

Slope = -0.0005

Intercept = 10.001

r = -0.009

$\bar{X}$ = Mean downwind protein particle concentration minus control concentration in thousand particles per cubic foot (tppcf).