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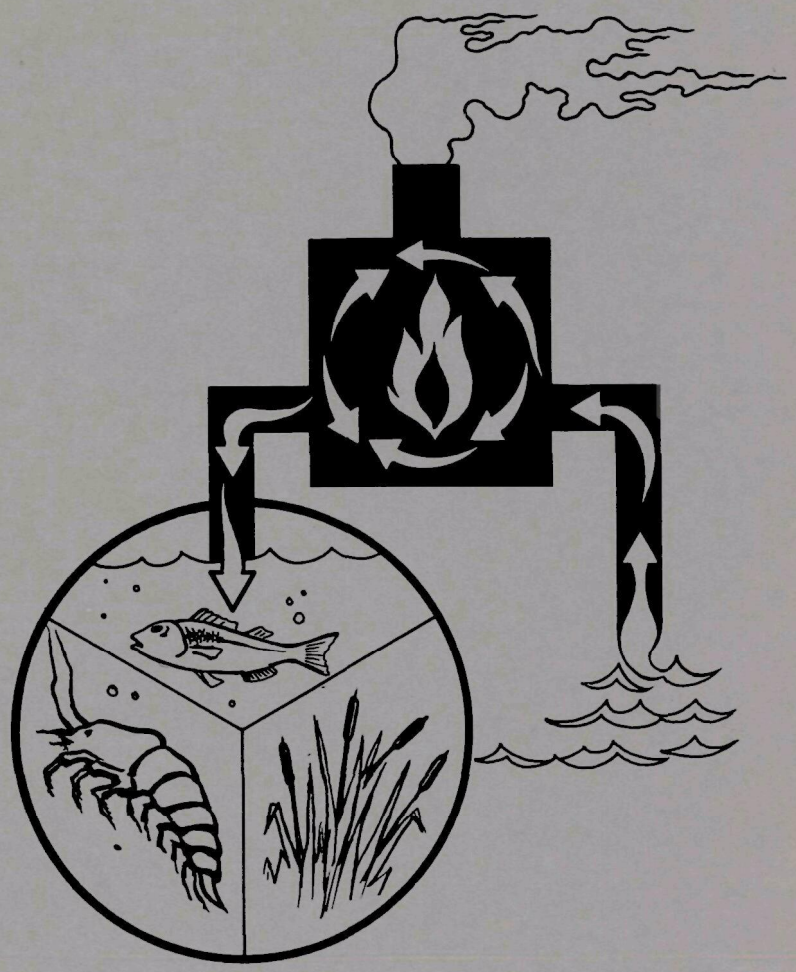
DEVELOPMENT AND DEMONSTRATION OF LOW-LEVEL DRIFT INSTRUMENTATION



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DEVELOPMENT AND DEMONSTRATION
OF
LOW-LEVEL DRIFT INSTRUMENTATION

by

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Post Office Box 2525
Knoxville, Tennessee 37901

for

Environmental Protection Agency

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ABSTRACT

Instrumentation for measurement of low level drift from cooling towers was developed. Emphasis was placed on the Particulate Instrumentation by Laser Light Scattering (PILLS) System which is capable of on-line measurement and, with incorporation of existing pulse height analyzer and mini-computer equipment, complete on-line data reduction. Complementary techniques of isokinetic sampling and sensitive paper sampling were developed and field proven. Feasibility was demonstrated for an infrared, in-line holographic system. The design principles and engineering trade-offs for the PILLS, IK, and sensitive paper techniques are described. Drift performance data are given for a small air conditioning cooling tower unit, two large mechanical draft cooling towers, and a natural draft tower.

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SECTION I

CONCLUSIONS

Preparation of this report has been difficult because of the breadth of the problem attacked and the number of solutions evolved. This most challenging project has required an iterative problem definition as we came to understand both the drift problem and the instrumental techniques we have applied to low level drift measurements. Presentation format and level for the developmental activities and results was chosen to give in each of the individual sections the introductory material, the data, and the detailed conclusions and recommendations to be drawn therefrom. This section is confined to general remarks on the drift problem as it is now understood and the applicability of the instrumentation available.

(1) The most meaningful parameter for concluding remarks on the PILLS system is the drift size range. There does not appear to be a lower limit for the PILLS system with regard to total drift mass emission level. The major effect of measuring lower levels of drift will be increased sampling time to acquire sufficient samples for statistical meaningfulness. The influence of other parameters such as air flow velocity, humidity, temperature, fog level, mineral concentration of the circulating water, etc., are discussed.

The present prototype PILLS system is entirely satisfactory for drift measurements on mechanical draft towers and spray pond coolers with low fog level. The minor improvements in the instrument which are presently being implemented will permit measurements from 50μm to 1000μm or larger. It is further concluded for the state-of-the-art drift measurement that measurements can be made immediately beyond approximately 100μm for fogging conditions which have been encountered in our experience.

(2) For situations where fog precludes measurements below, for example, 100μm, the double scattering volume PILLS system should be developed. Our preliminary investigations using rather unsatisfactory components demonstrates feasibility for relatively easy reduction by a factor of two to three the minimum particle size measurable in the presence of typical fogs. Thus, even with fog, it is entirely feasible with the double scattering volume instrument to record the particles from 50μm up. It is our present conclusion for hyperbolic cooling towers that the size range 50 to 150μm embraces the bulk of the drift emission. The drift emission for particles less than 50μm is even more negligible in terms of percentage contribution to the total emission for mechanical draft towers than for natural draft units.

(3) The independent, complementary drift measurement techniques of isokinetic and sensitive paper sampling deserve mention in conclusion. For estimates of integrated drift, and direct measurements of a particular mineral effluent, IK measurements are useful. For estimates of particle size distribution, with emphasis on the smaller diameter range, sensitive paper is useful. Both require lengthy data reduction.

Simultaneous application of the three complementary techniques was regarded as particularly important for initial studies even though the scope of effort was necessarily increased.

(4) Generally, it may be concluded that the responses of cooling tower manufacturers to environmental impact interests will have the effect of driving down the drift emission level via improvements in drift eliminator efficiency. The most effective reductions will be elimination of larger particles and it may therefore be expected that as drift levels go down so will the mean particle diameter. If drift emission levels of order 0.005% can be shown to have acceptable environmental impact, it can be expected that cooling tower utilization will increase. Brackish installations place severe requirements on drift elimination and measurement and this application should be studied with priority.

(5) Finally, our experience with this challenging and many-faceted problem has defined a clear and increasing need for a laboratory simulation facility for examination of cooling tower performance. One of the most severe difficulties encountered in instrumentation development was making measurements on operational towers although the field experience gained was valuable. The country needs a government-sponsored facility where drift eliminator designs and other cooling tower parameters can be studied with the repeatability and cost effectiveness of a laboratory environment.

SECTION II

RECOMMENDATIONS

In addition to the minor modifications and explicit calibration now in progress, the extension of the PILLS technique toward smaller drift particles (below approximately 100μm) in typical cooling tower fog backgrounds is the highest priority improvement in instrument performance per se. A factor of two to three reduction in minimum measureable diameter will probably permit measurement of all but a few percent mass emission even for hyperbolics. It is further recommended that pulse height analyzer-mini-computer electronic data processing equipment be employed for data acquisition and reduction, because the smaller, more frequently occurring drift components will become increasingly important.

However, the present PILLS system is adequate for measuring particles larger than ≈ 100μm in typical mechanical draft cooling tower fogs. Thus an important recommendation is to utilize the PILLS system with the complementary isokinetic and paper stain techniques for a careful and complete drift characterization program as soon as possible and simultaneously with drift outfall measurements, preferably on a brackish or simulated brackish installation. In addition to environmental impact assessment, an important part of such a program would be evaluation of improved drift eliminator designs.

SECTION III

INTRODUCTION AND BACKGROUND

Wet cycle cooling towers provide an attractive alternative for dispersal of large quantities of waste heat. These towers operate on the principle of heat transfer from hot circulating water to an atmospheric air flow. The heat transfer takes place via the large surface area presented to the air by a profuse distribution of small particles as well as via heat transfer fins which are the so-called fill material.

Cooling towers discharge heat into the environment in the primary form of latent heat as a result of the evaporative cooling process. Visual observation of cooling towers in operation also, under most conditions, indicates a substantial fog plume which results from condensation of the increased water vapor content of the air which went through the tower. It can be assumed that the vapor as well as the fog constitutes pure water and therefore does not generate a contamination pollution problem. However, the environmental impact of the hot, moist plume is important and this thermal pollution problem is under study.

The environmental problem addressed by this effort relates to the fact that the air in wet cycle cooling towers is in direct contact with the circulating water from which the heat is taken and thereby provides the opportunity for some of the particles generated in the process to be entrained in the air flow and carried through the tower and into the environment. It is known from simple Stoke's flow theory as well as more representative experiments that air flow velocities typically encountered in cooling towers are capable of carrying particles of several hundred microns into the environment. These particles, termed drift, constitute a pollution problem since they will have to first approximation the concentration of minerals which is found in the circulating water. For the important application to brackish water installations with high mineral content, the mineral residue can constitute a severe environmental impact problem if the level of tower drift emission is high. An example is illustrative.

A number that has become associated with the drift phenomena is 0.2%; i.e., the drift emission rate is 0.2% of the circulating rate. This number originates with early developmental studies associated with cooling towers perhaps even before efficient drift eliminator designs were put into practice. It is easily shown that a very large cooling tower having 500,000 gallons per minute for its circulation rate would generate a salt deposition of 7.5 tons per hour if one uses the 0.2% fraction for drift emission and assumes the normal salinity of 30,000 ppm for sea water. Clearly, this environmental impact is severe.

It has been presumed for some time that modern cooling towers with efficient drift eliminators have far lower levels of drift. However, prior to mid-1970 there existed no proven techniques for measuring low levels of drift. In early 1970, Environmental Systems Corporation addressed the problem of measuring low level drift as a result of interests expressed by The Marley Company. Feasibility was demonstrated on a very small scale

for laser light scattering and holography techniques by the mid-part of 1970. Shortly after feasibility of these techniques was demonstrated to a number of private utility and EPA personnel a proposal was submitted to the Environmental Protection Agency for the purpose of providing a demonstration grant to the ends of showing feasibility to those concerned with the drift problem. Funds were approved and work was formally initiated for the demonstration grant in March 1971. The development culminated in a demonstration experiment performed on a mechanical draft cooling tower located at the Oak Ridge National Laboratories in Oak Ridge, Tennessee on September 28, 1971. Approximately eighty persons from across the country intimately concerned with the drift problem were in attendance of this special demonstration.

Before proceeding with the discussion of the instrumentation developed, it is worth reviewing the requirements which were placed on the drift measurement system as they were understood in 1970. At that time it was presumed that the drift particles were several hundred microns in diameter. It was further estimated that the drift percentage was at least one order of magnitude lower than 0.2% and that the concentration of the mineral content in the drift particles was identical with that of the circulating water.

Numerous instrumental techniques were considered which had potential. In addition to the obvious considerations of accuracy, reliability and cost, it was decided to pursue the technique(s) which had the potential to develop into an on-line monitor and, more important, technique(s) which would resolve the particle size distribution. Particle size distribution is of fundamental importance because the dynamical behavior of the contaminating drift particles is different for different sizes, both in the tower and when they leave the cooling tower and are placed in the environment. Large particles will fall out more quickly. Sufficiently small particles having sufficiently low mineral concentrations may even evaporate to residues which are airborne essentially indefinitely. Of course, the total amount of particulate matter can be obtained by integration over the particle distribution.

With these factors in mind, two electro-optic techniques - that of laser light scattering and in-line holographic recording - seemed the most viable. The scattering technique has the most potential for a truly on-line measuring capability and the most potential for extension to smaller and/or larger particles than the few hundred microns assumed. Although holography generates a permanent record of the particle field, it can be argued that the two-step holographic recording and reconstruction process is little better than photomicrography using a pulsed light source for this application. It was concluded after feasibility had been demonstrated for both to emphasize Particulate Instrumentation by Laser Light Scattering, or the PILLS system. The next section discloses the principles of this system. The fifth section discloses the principles of two complementary techniques which we have employed in the field to measure drift as well as a disclosure of the holographic technique and compares all these techniques for relative merits. Section VI summarizes drift measurements which were performed in preparation for the Oak Ridge demonstration.

SECTION IV

PARTICLE INSTRUMENTATION BY LASER LIGHT SCATTERING (PILLS) SYSTEM

BASIC PRINCIPLES

The essential operating principles of the PILLS system can be efficiently explained with use of Figure 1. A laser emits pulses of radiation with a wave form having the shape as shown in inset A. Peak powers of 12 watts of infrared radiation at 9040 Angstroms are emitted by a gallium arsenide junction laser diode. A most important innovation employed in the fabrication of the PILLS system has been utilization of the gallium arsenide laser diode, which permits design of a very compact and reliable device. Figure 2 shows a photograph of the laser diode mounted in the optical support as well as an additional diode shown on the machinist's scale for size comparison. The copper tube in front of the diode lens directs dry N_2 which is used to continuously purge both the laser and detector components.

To our knowledge this is the first utilization of the laser diode in this application. The peculiar emission properties of the laser diode necessitate collection of the light to realize a collimated beam. Although in some of the initial work a rather complicated collimation system of spherical and cylindrical lenses was used, it proved acceptable and far more convenient to obtain essentially a collimated beam with a single microscope objective as shown in the mount in Figure 2.

Referring again to Figure 1, a scattering volume V_S is defined by the intersection of the laser beam (3x4mm) and a detector acceptance cone. The acceptance cone is defined in the present configuration by two apertures A_1 (64mm), the entrance aperture, and A_2 (25mm), the exit aperture which precedes a narrow band interference filter (100A) and a photomultiplier detector (S_1 photocathode). When a particle of diameter d is within V_S when a laser pulse occurs, light is scattered through the collection system to the photodetector which provides a pulse of current proportional to the scattered light intensity. This current pulse is amplified by an integrated circuit preamplifier which broadens the pulse to a width more convenient for processing ($\approx$1us). The IC is followed by a driver circuit suitable for launching the pulse into coaxial cable.

The essential information is in the height or amplitude of the pulse generated at the output of the coaxial cable at point B. Beyond point B the essential information may be processed in a variety of ways depending upon the circumstances of the particle field being examined - this is discussed later.

Before examining the characteristic wave forms that appear at B it is most important to present two essential design features of the PILLS system relating to the scattering volume V_S. First, the scattering volume is sufficiently small that particles in the range of interest will exist in the scattering volume only one at a time. In more mathematical

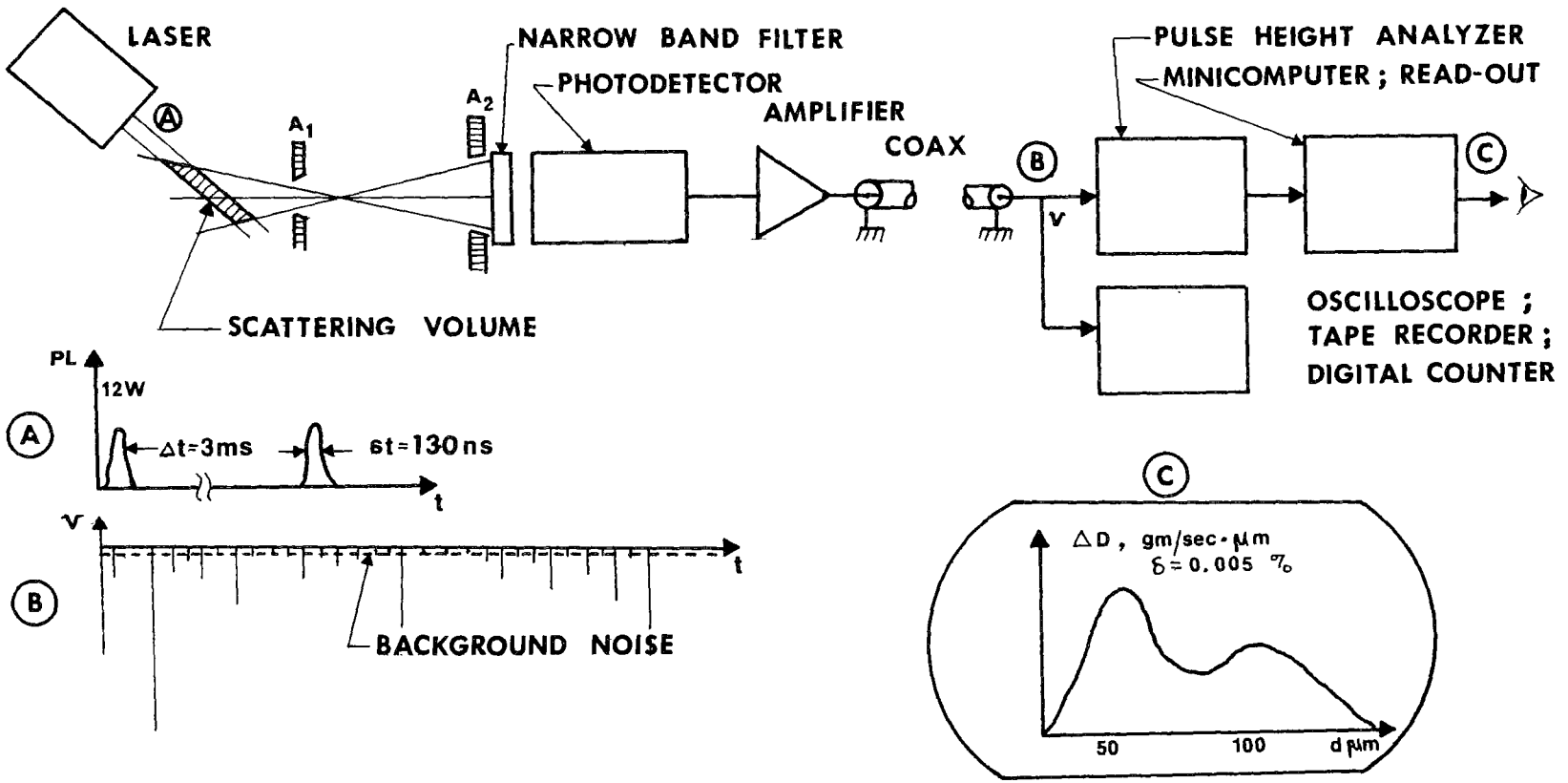

FIGURE 1

PARTICLE INSTRUMENTATION VIA LASER LIGHT SCATTERING

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KNOXVILLE , TENNESSEE

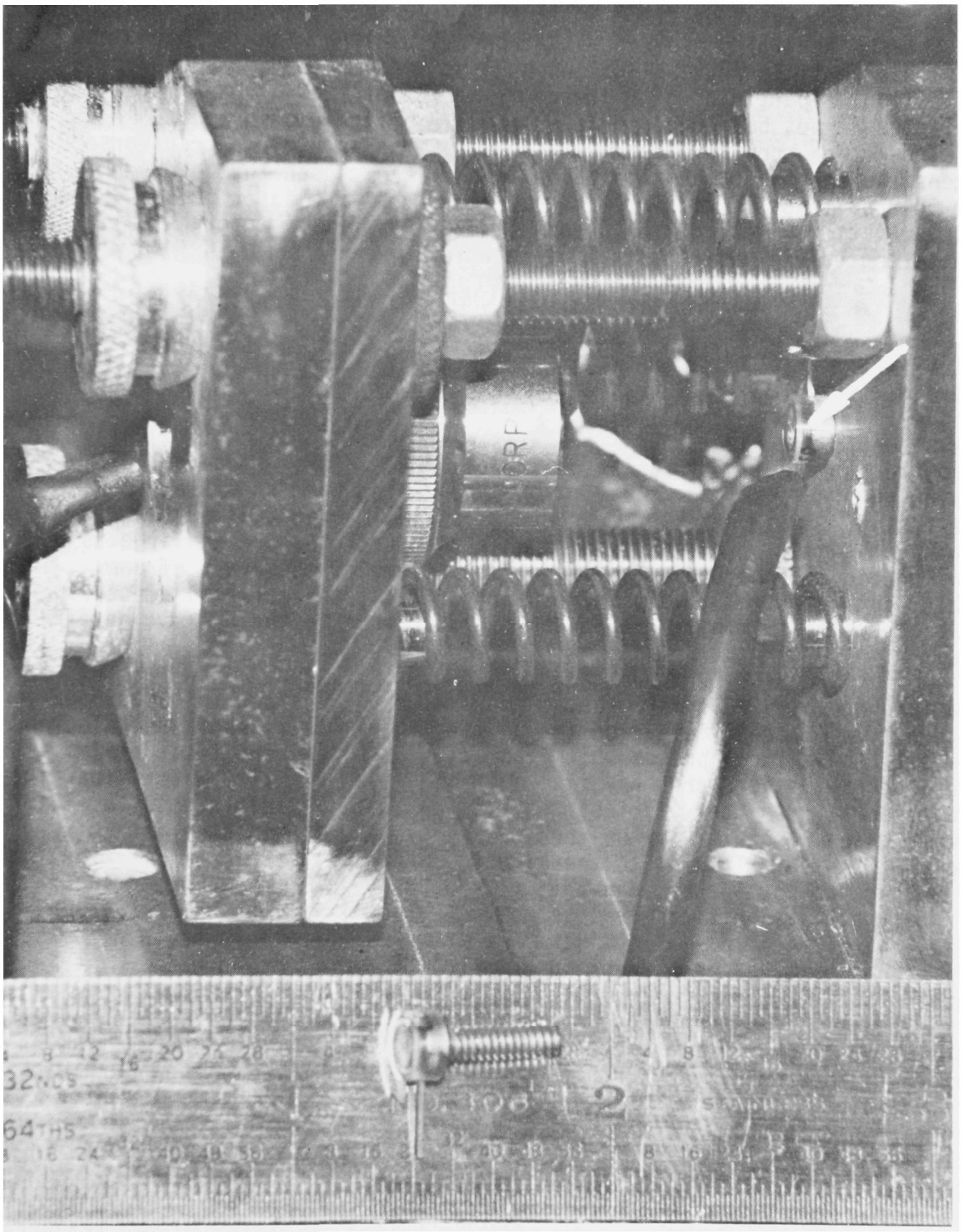


FIGURE 2
PN LASER IN OPTICAL MOUNT

terms, the probability of finding a particle in the range of interest in V_s at any instant of time is significantly less than unity. This has the substantial consequence that one is dealing with the phenomena of single particle scattering. When light reaches the detector from a collection of particles of different sizes, the sizes of the individual particles cannot be deduced from a simple amplitude measurement. A related design consideration is that the scattering volume transverse dimensions and the pulse repetition rate are so chosen that a given particle will not be counted twice by two successive laser pulses. The pulse repetition rate $f = 1/\Delta t$ and the flow velocity $\vec{v}$ through the scattering volume must satisfy the relation

$$v\Delta t > d_t \qquad (1)$$

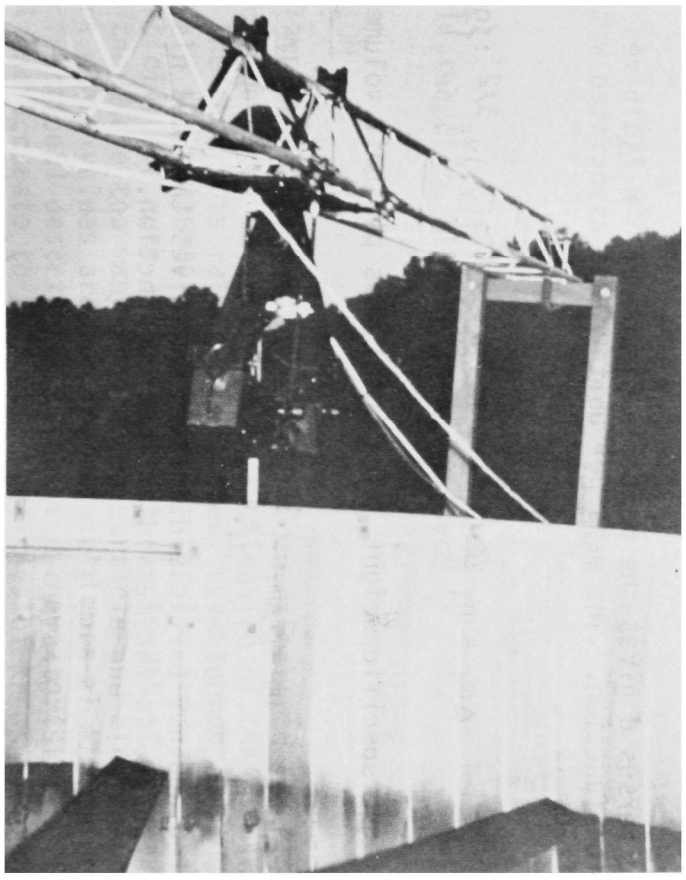
where d_t is the appropriate transverse dimension of V_s.

The second fundamental point is that the scattering volume is clearly presented to the flow rather than the alternative design concept of taking particulates from the flow and presenting them to an internal scattering volume. The latter concept is viable when the particles are small and dense. It is not viable when the particles are as large as a few hundred microns and occur in a given volume of the order of one cubic centimeter relatively infrequently. Thus, the external scattering volume presents a minimal aerodynamic disturbance to the dynamic particle field.

Examining now the wave form that appears at point B shown in inset B of Figure 1, a typical yield from the scattering volume is sketched. There are small background pulses which can occur each time the laser emits. These occur if there are many small particles in V_s. If few small particles are present, or better, if their density and size is sufficiently small, then the lower sensitivity of the instrument is determined by detector/amplifier noise. Turning to the signal of interest, a random distribution of voltage pulses larger than the background/noise is shown occurring at a rate that is significantly less than the repetition rate of the laser. Also, there are more small pulses than large pulses. This train of pulses represents what has been found to be descriptive of the particle distributions observed in actual cooling towers.

It must be clearly noted that the design considerations of the instrument relate to the particle distribution and the flow in which these particles are entrained. It is also important that the mechanical and electrical design considerations of the system take into account the extraordinarily hostile-hot, humid and turbulent-environment which can be encountered in cooling tower flows.

Figure 3 shows the final prototype configuration installed on the traverse rail above the mechanical draft tower used for the Oak Ridge Demonstration. In this configuration, the electro-optical properties of the instrument permit measurements from approximately 80μm to over 1,000μm in subdued light and in a light fog background with a typical sampling time of approximately thirty minutes per station. The instrument was so configured because of knowledge of the particle distribution being examined in the



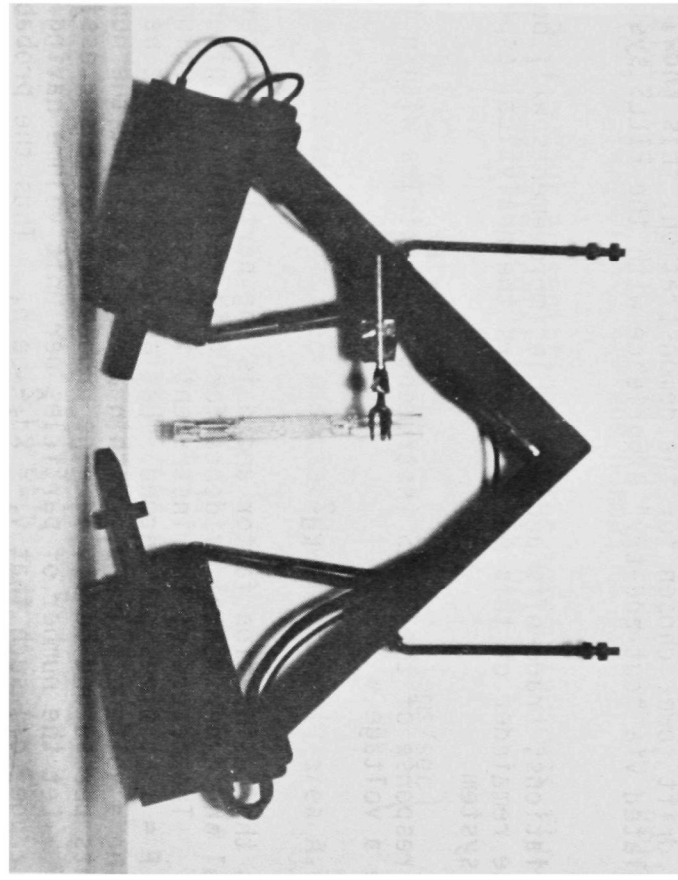


FIGURE 3 PILLS SYSTEM

mechanical drift tower chosen for the demonstration; this knowledge was accumulated via "cut-and-try" experience with the PILLS system itself.

Design variations, trade-offs and desirable improvements will be presented below. The remainder of this section covers the analytical aspects of the PILLS system.

The basic response of the PILLS instrument to particles within V_S is to produce a voltage v

$$v = Kd^2 \tag{2}$$

where K is the calibration factor and d is the particle diameter. The theoretical and experimental evidence for this relation is given in "Calibration." The nature of the instrument is to sample the volume V_S at a rate $F = 1/\Delta t$ times per second. Let a successful event be defined as obtaining a voltage pulse v_i (within a range Δv_i) and the number of these events per second be $f(v_i)$. The probability of a successful event is $f(v_i)/F$. Let the number of particles per unit volume having d_i (within a range d_i) such that $v_i = Kd_i^2$ be n_i. Thus the probability of the same successful event is $n_i V_S$. Equating these probabilities gives the basic describing equation for the instrument:

$$n_i V_S = f(v_i)/F = f(v_i)\Delta t \tag{3}$$

n_i plotted versus d gives the particle histogram. $n_i/\Delta d$ gives the particle distribution function. The mass per unit volume associated with the ith size particles is

$$\Delta m_i = n_i \frac{\pi}{6} d_i^3 s = \frac{\pi}{6} \frac{s}{K^{3/2}} \frac{\Delta t}{V_S} f(v_i) v_i^{3/2} \quad \left\{\frac{gms}{ft^3}\right\} \tag{4}$$

where s is the specific weight. The total mass per unit volume is

$$m = \sum_i \Delta m_i = \frac{\pi}{6} \frac{s\Delta t}{K^{3/2} V_S} \sum_i f(v_i) v_i^{3/2} \quad \left\{\frac{gms}{ft^3}\right\} \tag{5}$$

When plotted against particle diameter, Δm_i gives the mass histogram. $\Delta m_i/\Delta d_i$ versus d_i is the mass distribution function.

The flow rate is simply

$$Q = VA \qquad \left\{\frac{ft^3}{sec}\right\} \tag{6}$$

where V is the flow velocity and A is an area normal to the flow velocity vector. The quantity of material carried by the flow is

$$D = mVA \qquad \left\{\frac{gms}{sec}\right\} \tag{7}$$

For the PILLS instrument the area substituted is A_t, the projection of the scattering volume onto a plane normal to $\vec{V}$.

A basic data output presentation for the integrated mass flux is to give for each "j" measuring point the quantity D/A_t:

$$\left.\frac{D}{A_t}\right|_j = \frac{\pi}{6}\,\frac{s\Delta t v_j}{K^{3/2}V_s}\sum_i f(v_i)v_i^{3/2} \qquad \left\{\frac{\text{gms/sec}}{\text{ft}^2}\right\} \tag{8}$$

The drift emission in gms/sec associated with the "j" area A_j is

$$D_j = A_i\left(\frac{D}{A_t}\right)_j \tag{9}$$

and the total drift emission in gms/sec is

$$D = \sum_j D_j = \sum_j A_j\left(\frac{D}{A_t}\right)_j \tag{10}$$

Equations 8, 9, and 10 are easily converted to give, respectively, the point, area, and total mineral emissions by multiplying both sides by the total mineral concentration of the circulating water c or for a specific mineral such as Na, Ca, Mg, by C_ℓ, the concentration of the ℓth mineral component.

Finally, the drift percentage is

$$\delta = \frac{D}{R} \times 100\% \tag{11}$$

where R is the circulation rate in gms/sec.

CALIBRATION

In principle, the relation between particle diameter d and PILLS system output voltage v may be predicted by application of the Mie scattering theory. The theory is rather complicated, even though considerable reduction in the mathematical complexity results from the fact that the drift particles are much larger than the wavelength of the laser radiation However, there are too many scattering particle and electro-optic system parameters whose values are too inaccurately measureable to permit an accurate functional description of the v-d characteristic. It is more practical and accurate to introduce particles of known size and composition into V_s and measure the v-d characteristic explicitly for a given system configuration.

Unfortunately, time pressure did not permit the evolution of an explicit calibration apparatus. Calibration was realized for the instrument by comparing its data with a complementary measurement technique, isokinetic

sampling, described below. With isokinetic sampling as with the PILLS system after integration over the particle distribution, one measures the drift water mass per unit volume. If the Kd^2 relation of Equation 2 is assumed, simultaneous PILLS-IK measurements yield K. The calibration analysis is given in the appendix.

Justification of the $v \propto d^2$ relation is based on theoretical and experimental evidence. Rather than present Mie theory results, a simple physical model may be employed as a plausibility argument. The transparent, spherical drift particles collect and converge the incident radiation analogously to a thick spherical lens. The "focal length" may be shown to be proportional to the particle diameter. Thus the collected and "focused" light diverges with an angle independent of d. For water particles having index of refraction of 1.33, the angle θ_{max} between the incident light direction and the scattered light direction is approximately 45°. A simple experiment was performed with a widely disperse particle distribution of drift water particles which substantiated this model in that little scattered radiation was detected beyond $\approx$50°.

The generality of the $v \propto d^2$ relationship is further supported by the data of Figure 4. The scattering particles for this experiment were semitransparent Apiezon wax particles melted onto a glass flat. The laser used was a pulsed argon ion device filtered to yield $\approx$ 0.5W of green light at 5145 Angstroms. The detector was a standard silicon photodiode. (Clearly, a constant K derived from Figure 4 is not directly applicable or relatable to the PILLS system.)

This evidence supports the $v \propto d^2$ assumption necessary for implementation of the IK-PILLS implicit determination of the calibration factor K. Considerable confidence in this implicitly-determined value is generated as a result of the agreement between the three complementary drift instrumentation techniques when applied to the Oak Ridge Tower (See Section VI.) Of particular importance is the agreement between the PILLS and sensitive paper data in the location of distinguishing features of the particle histogram.

Notwithstanding the general agreement between independent measurements and the confidence in K implied or the evidence supporting the $v \propto d^2$ relation, it is highly desirable to explicitly calibrate the PILLS system with particles of known size and composition. This activity is being pursued as an extension of the present effort and will be reported separately. These experiments are expected to confirm the $v = Kd^2$ relation as well as provide data on the effects of high mineral concentrations as encountered in brackish water applications of cooling towers.

A monodisperse stream of particles from sizes as small as 15μm through 500μm can be generated by vibrating capillary techniques (1). Smaller particles can be produced via vibrating orifice techniques (2). Both exploit the inherent hydrodynamic instability of a stream of liquid moving through a viscous medium. These techniques require a substantial amount of experience and a nominal amount of equipment and are well-documented in the literature.

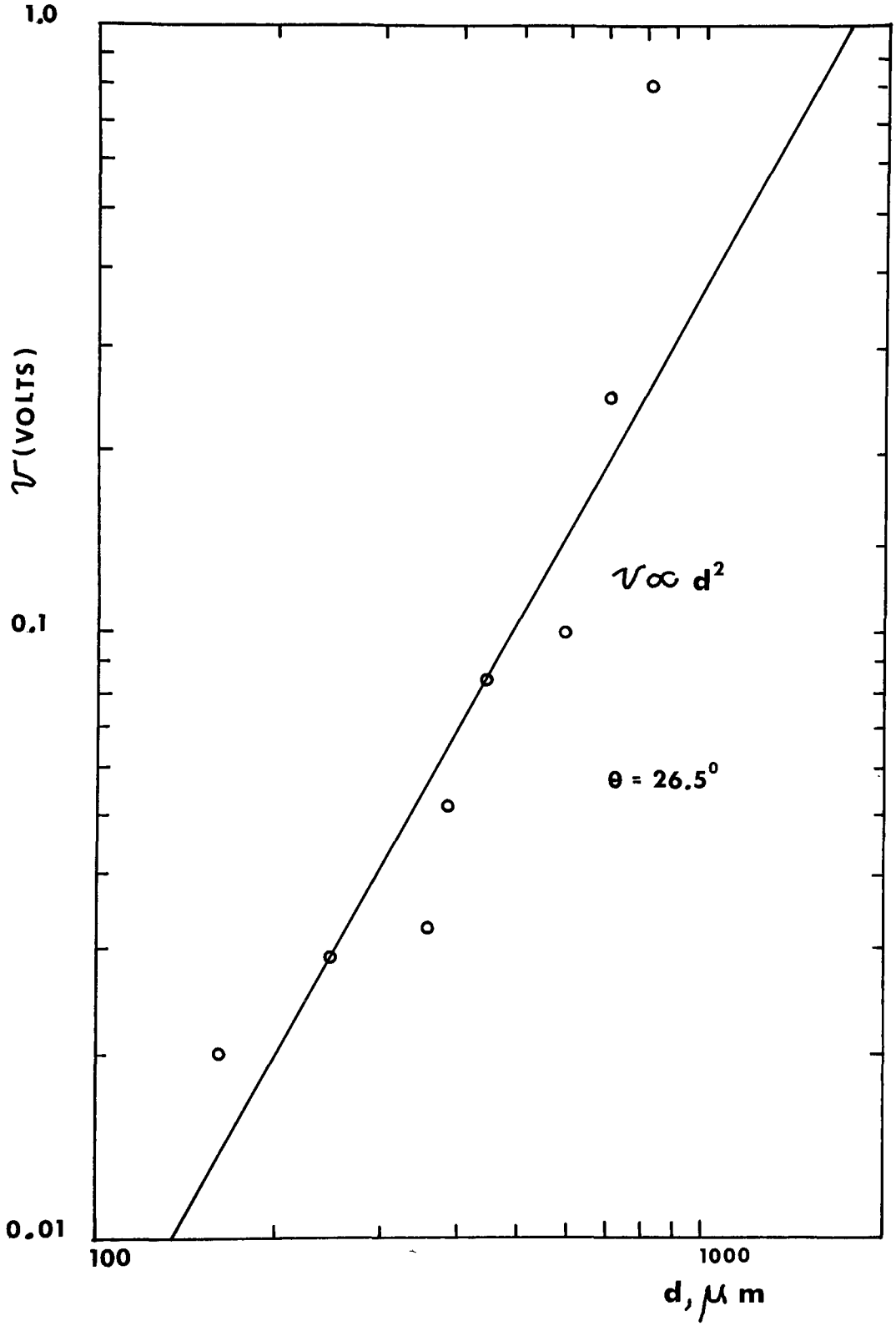


FIGURE 4

AR II LIGHT SCATTERING BY APIEZON WAX PARTICLES

It should be pointed out that it is well known that there are available mono-disperse glass beads which are in the size range of interest for the calibration of the instrument. Such particles were used to obtain a rough estimate of the calibration factor but were not used for the primary calibration. They may not adequately simulate the water particles because of the differences in index of refraction and surface conditions.

SIGNAL PROCESSING

Consider again the wave form presented at point B in Figure 1 in which the particle's size is represented in the voltage amplitude. The pulses occurring at random times and with random amplitudes must thus be analyzed to give the particle distribution and integrated mass of the drift phenomena under examination. Field experiments with preliminary PILLS prototypes on mechanical draft towers indicated that drift particles could be smaller than 50μm and larger than 500μm. However, very few particles greater than 500μm were observed and a small fraction of the drift emission mass was less than 50μm. It was thus assumed that the most important size range was approximately 50-500μm.

Preliminary experience also indicated that the typical fog background present under most cooling tower operational conditions yields a quantity of light that is proportional to the scattering volume and whose magnitude may be larger than the yield of a single drift particle. Unfortunately, the fog voltage cannot be completely subtracted out because of random pulse-to-pulse variations in the laser intensity and, consequently, the fog effively sets a lower limit on the drift particle size which can be measured. One way to reduce the fog problem is to reduce the scattering volume even below the limits wherein single particle scattering obtains for the drift particle distribution. The trade-off in this reduction is that one must wait for a longer period of time to collect enough voltage samples to be statistically meaningful.

Cut and try iterations on the instrument configuration design for the particular particle distribution and fog level associated with mechanical draft towers led to a compromise of a minimum measurable particle of, typically, 100μm and a data collection time of 30 minutes. In the absence of fog, the system - in its present configuration - is limited by electronic noise to 80um. This lower limit can be easily reduced to a few microns by reconfiguration and optimizion of the laser-detector-amplifier components.

The rate at which data pulses are collected with the present configuration is, for drift particles larger than approximately one hundred microns, one count approximately every second for a mechanical draft tower. Consequently, it was convenient for data collection to set the trigger level on a precision oscilliscope to a voltage value corresponding to a particle diameter of, for example, 100μm and then measuring the time required to collect ten pulses corresponding to particles larger than 100μm.

These pulses were recorded in a multiple exposure fashion with the oscilloscope camera. Usually, several photographs having ten pulses each are made. Figure 5a shows a typical photograph thus obtained. (Figure 5b is a real time recording wherein each laser pulse is identifiable and was used for a particle distribution having roughly 10^3 times larger mass flux.) This recording technique is suitable for low count rates and has the inherent advantage of permitting measurement of the pulse height directly from the oscilloscope photographs.

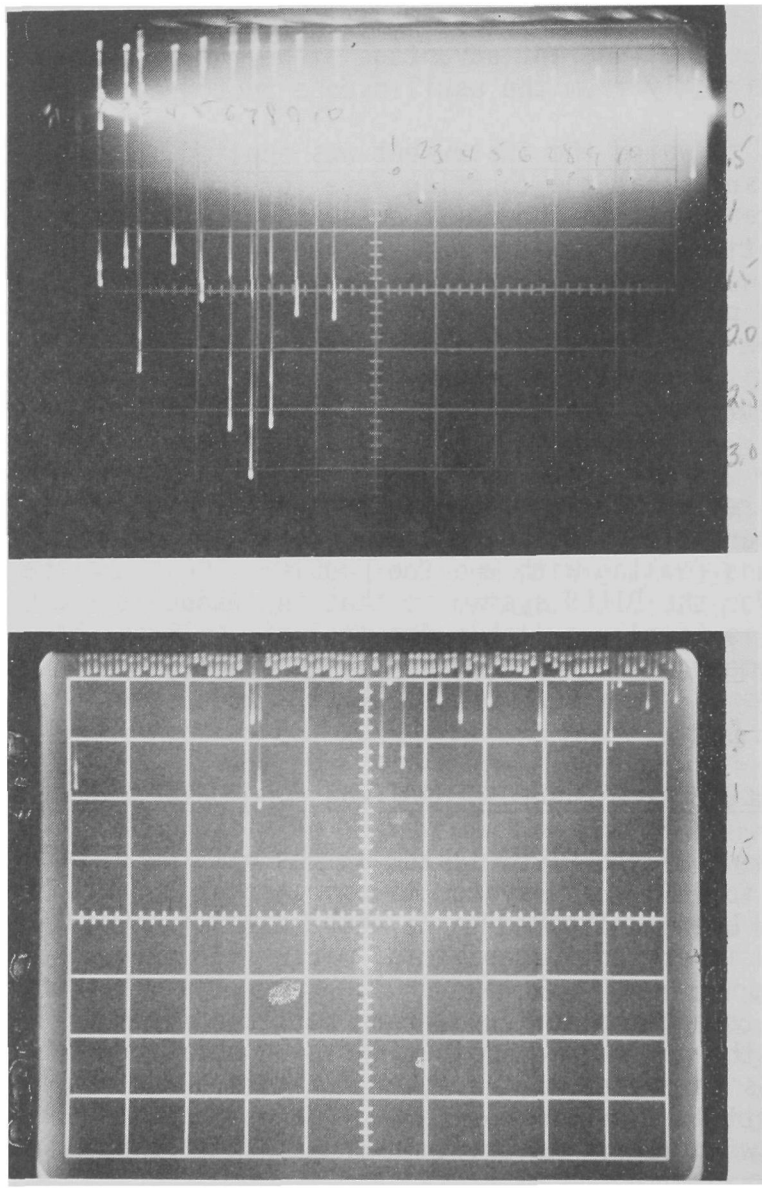
In several situations to which the instrument was applied, the fog level was low enough such that the counting rate for small particles contributing significant mass to the drift emission was sufficiently rapid that stopwatch time measurements proved inadequate. For one of those situations, it was possible to utilize a digital counter which counted the number of pulses exceeding a preset level in a given period of time. Although the more frequently occuring particles were recorded with this technique, it was still necessary to sample for approximately thirty minutes to obtain the same statistical accuracy for the large particles as before.

These considerations reflect the engineering trade-offs made to accomodate specific particle distributions as well as discovery of these distributions and dealing with the fog problem. However, the most important advantage for the PILLS system is that the random pulse train generated at point B is ideally suitable for analysis by available pulse height analyzer equipment which has been developed primarily as nuclear instrumentation. This is described more fully in a later section.

SUMMARY OF PILLS DEVELOPMENT AND RECOMMENDATIONS FOR FURTHER WORK.

The state of development of the PILLS system at the writing of this report may be summarized as follows. The system is operational and has been field proven. It has been configured for a field-determined particle size distribution and is presently capable of measuring under conditions of minimal fog from approximately 80 to over 1,000μm. The size range may be extended both toward smaller and larger particle sizes giving due consideration to the particle distribution to be measured and the background fog. It is estimated that a lower limit of a few microns can be achieved. Particles larger than 1,000μm do not appear to be of significant interest with regard to drift instrumentation although they could be easily measured with the PILLS system.

The usefulness, design adequacy and field worthiness as well as limitations of the PILLS system are best supported by the data on operational cooling towers reported in Section VI and no further performance claims are given here. It is important to state, however, that the present configuration is directly suitable for drift measurements on all cooling towers or spray ponds for which particles larger than, typically, 100μm constitute the principle concern. This lower limit is set by instrument configuration in conjunction with fog background usually encountered with cooling towers but can be reduced.



DOWN-WIND
(SAMPLED)

UP-WIND
(REAL TIME)

FIGURE 5

TYPICAL PILLS DATA

However, as should be expected with a developmental activity, there are several important areas which will profit with further effort. These are listed in the following discussion in the order of their importance to the drift measurement problem as it is now understood. Numerous minor improvements, such as reduction of light background, cooling of critical components, and design refinements, will yield greater convenience in data interpretation and in field operation and are straight-forward in reduction to practice.

(1) Explicit Calibration. The realization of vibratory capillary or orifice particle generators needs to be accomplished and applied to generation of the v_0 - d characteristic of the device in a specific, optimized configuration. It is not expected that the relationship will depart materially from Kd^2 but nevertheless needs explicit verification for water particles closely simulating actual drift. This activity is in progress.

(2) Fog Suppression. The fog yield can be reduced by reduction of the scattering volume with the cost of increased sampling time. Thirty minutes now typical for a sampling period is regarded as long when the basic sampling rate capability of the instrument and, specifically, pulse height analyzer processing equipment, are considered. But larger scattering volumes cannot be used because the fog yield can be as large as that from a small drift particle. This background cannot be simply subtracted out for the single V_S because the fog yield fluctuates.

Some preliminary design consideration and experimentation has been given to a so-called double V_S instrument whose principle is as follows. The laser beam proceeds as in Figure 1 but illuminates two scattering volumes. The size of the scattering volumes and the overall system transfer gain are adjusted such that for a homogeneous fog particle distribution - but no drift particles - an identical output voltage is realized. These two voltages are then fed to a differential amplifier. If no particle is present in either scattering volume a reading of zero is realized. If a particle is in one of the scattering volumes then the voltage realized for that particular channel is larger and the difference is proportional to Kd^2. This system has the capability of resolving smaller particles in the fog background as long as the drift particles are substantially larger than the fog particles whose mean diameter is probably $<5\mu m$ for cooling towers because the droplet formation time is much shorter than for meteorological fogs whose mean diameters are typically 10-20μm (3). The scattering volumes can be designed larger (but not large enough to violate the single particle occupancy requirement) with the important result that the data collection rate can be increased. Thus, a double V_S instrument permits resolution of smaller particles and more rapid data collection.

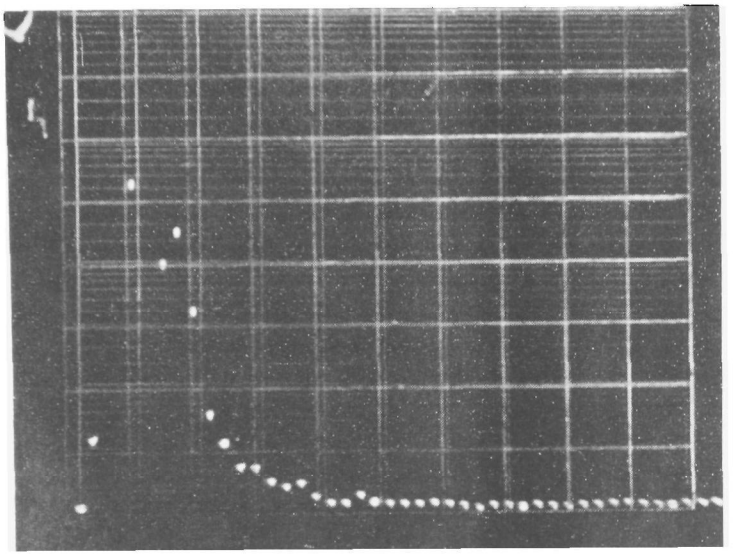
The initial experiments which were performed met in marginal success because photomultipliers were used which had very poor noise characteristics The noise in each channel of the detector circuits is uncorrelated and thus cannot be directly subtracted out whereas the fog yield is obviously

correlated and can be subtracted. The preliminary experiments do indicate feasibility for photomultipliers or other detectors having significantly lower noise. These - or alternative - design considerations for fog yield suppression must be pursued as the interest in particle sizes shifts toward smaller particles which are present in a large background of fog.

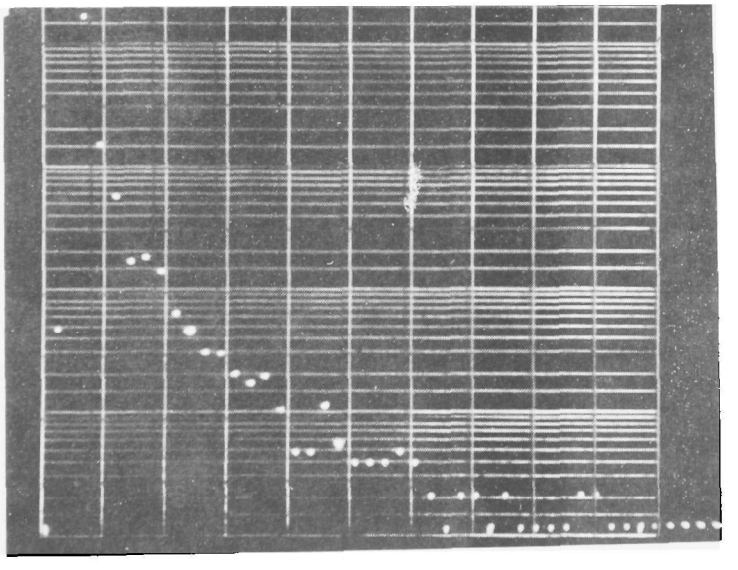
(3) Pulse Height Analyzer/Mini-Computer Processing. Pulse height analyzer instrumentation generates the voltage height distribution by sub-dividing a voltage range of typically 0-10 volts into, for example, 512 channels or voltage increments and then storing in each channel's digital memory the number of counts observed in a sampling period. In some units, 10^6 counts can be stored in each channel. The number of counts per channel then can be directly displayed in an analog presentation on a CRT as the voltage histogram or the voltage distribution function. But because of the digital nature of pulse height analyzer equipment, the count data are already coded in a digital form and are suitable for presentation to a plotter or a teletypewriter system which will plot or print out the number of pulses per channel.

Most important to the automatic processing consideration is that the output of a pulse height analyzer, being digital, is suitable for direct insertion into digital computation equipment, especially the new generation of mini-computers. Thus, the complete integration of the laser scattering system with a pulse height analyzer appropriately interfaced with a mini-computer could produce a readout as shown in inset C of Figure 1 wherein the parameter of interest, grams per second emitted by the tower in a given micron size range is presented on, for example, a cathode ray tube or on a digital plotter. Simultaneously with a presentation of the particle distribution the mini-computer can be programmed to generate the integrated amount of drift water leaving the tower per second and/or to produce a direct visual display of the drift percentage. Clearly, this system could be employed in an operating power station to provide an automated readout of drift performance of a given tower. It could be used for rapid data acquisition for tower certification. Still another application would be as an integral part of a laboratory cooling tower simulation facility which would permit convenient testing of drift performance.

It is to be recalled that the capability of providing an on-line readout of the drift parameters of interest was a prime consideration in choosing the PILLS system. A pulse height analyzer was incorporated into the Oak Ridge Demonstration of September 28 and Figure 6 shows a CRT presentation of the voltage height distribution.



LINEAR



LOG

FIGURE 6

PULSE HEIGHT ANALYZER DATA
(CRT PRESENTATION)

SECTION V

COMPLEMENTARY DRIFT MEASUREMENT TECHNIQUES

Rather than invest all our effort in the development of the PILLS system, it was considered advantageous from an engineering viewpoint to develop three other drift measurement techniques to complement the PILLS system and to provide thereby a check on its accuracy and applicability Several field tests were performed during the course of this development and it was possible for us to develop two of the other techniques beyond laboratory feasibility to the point of field use. In the order that they have been utilized and developed they are: (1) isokinetic sampling, (2) sensitive paper sampling, and (3) in-line holography. The principles of each of these will now be discussed.

ISOKINETIC SAMPLING

Operational fresh water cooling towers have a substantial mineral content in the circulating water, generally greater than a few tens of ppm of elements such as calcium and magnesium. (Of course, the concentration of sodium and chlorine for brackish water towers would be much higher, of the order of 30,000 ppm.) Analytical chemical techniques, particularly atomic absorption spectroscopy, permit the determination of material concentrations as small as a few parts per billion for magnesium, for example. Thus, if one isokinetically samples a volume of air moving through the tower and extracts from it the drift water and from the drift water the mineral residue and assumes that the concentration in the drift water is identical with that of the circulating water, then a measure of the trapped mineral residue yields the amount of drift material in the sampled volume. From this the total drift emission is realized by numerical integration via an appropriate area segmentation of the tower based on the measured air velocity profile.

The terminology "isokinetic sampling" relates to the measurement of air flow in the following way: air is drawn into a sampler tube having the kinetic energy of a fluid element identical with that which existed had the tube not been there. If it is assumed that the density and temperature of the air do not change upon being drawn into the tube, this reduces to maintaining equality between the velocity of the air flow into the tube and the flow velocity in the absence of the tube at the point of measurement. Procedurally, one measures the mean flow velocity at the test point with, for example, a vane anemometer, and then adjusts the volumetric flow rate through the sampler such that the mean velocity in the sampler tube inlet is equal to the flow velocity. Figure 7 indicates the elements of an isokinetic sampling system including the vacuum pump, integrating gas flow meter and sampler head.

Isokinetic sampling of dry particulate matter as, for example, in power plant stacks, has been realized for several years and is a standard and

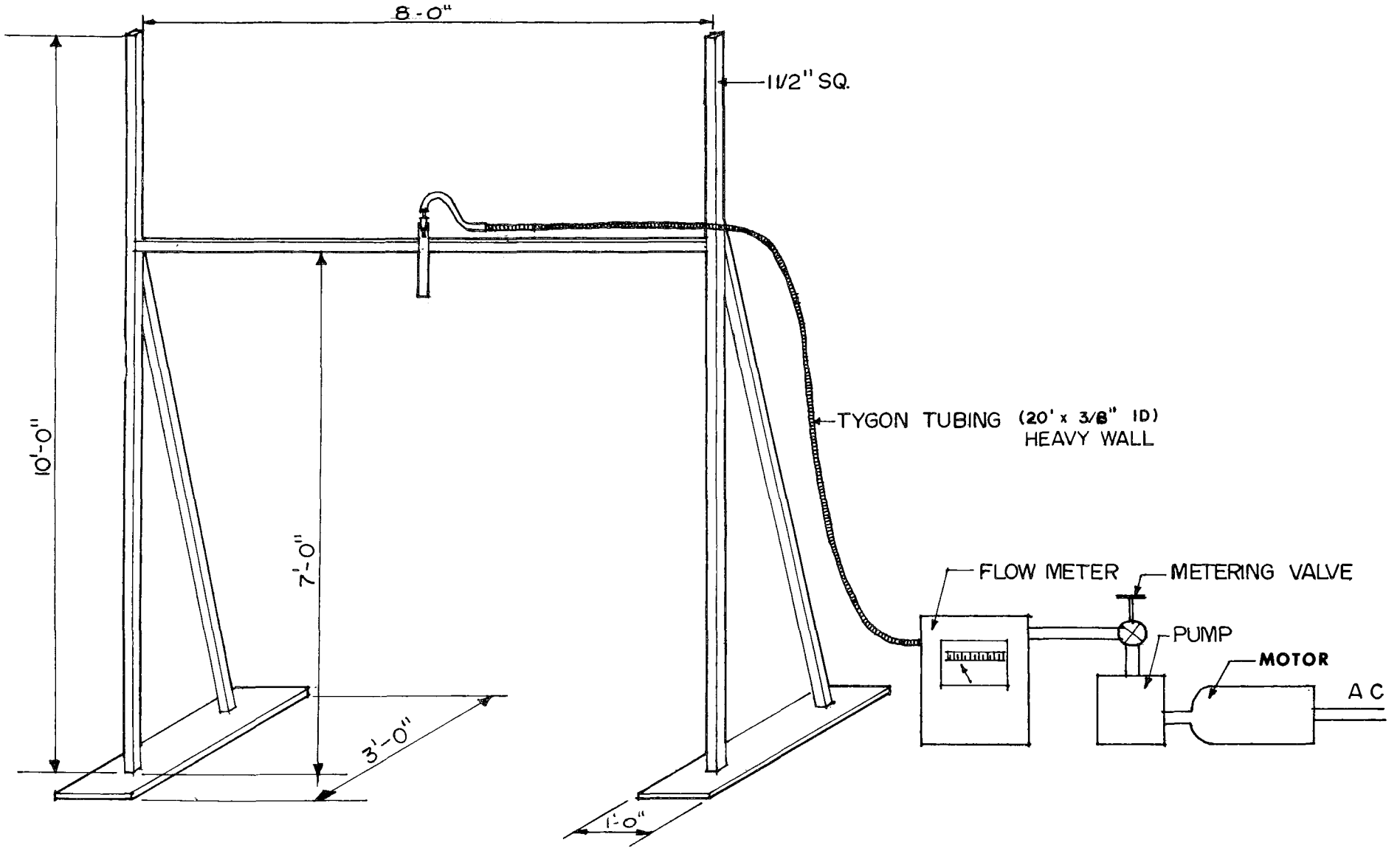


FIGURE 7
ISOKINETIC SAMPLER SYSTEM

accepted technique. These sampling heads are generally constituted of a 1/4" to 1/2" entrance diameter probe tube followed by a filter paper system which collects with high efficiency particulate matter larger than a few microns. As a matter of interest, the so-called "collection or trapping efficiency" of paper type filters is minimum for particles of approximately 0.3um diameter. Larger particles are trapped by inertical impact and smaller particles are driven onto the filter fibers by random Brownian motion. A standard filter paper has been Whatman No. 1 and can have trapping efficiency for dry 100μm particles approaching 100% (4).

We examined the straight-forward extension of these sampling techniques to drift measurement and assumed that the mechanism of trapping would be particle impingement and subsequent evaporation of the water, leaving the mineral residue on the filter. For analysis, the filters are then burned in an oxygen atmosphere; the burned residue is dissolved and finally analyzed by atomic absorption techniques. These measurements proved inadequate and inaccurate for two basic reasons. First, the amount of magnesium and calcium in the filter paper is of the order of a few micrograms and varies substantially from paper to paper and even within the same paper. Consequently, one must sample for a substantially long time to acquire a quantity of residue material significantly larger than the background of the filter.

Second, it was found that when the filters were introduced to the moist hot atmosphere of the cooling tower that questions arose with regard to the holding efficiency of the filters. It is useful to note at this point that if the quantity of drift water per cubic foot is defined as one unit, then by orders of magnitude the quantity of water in the form of fog will be 10 units and the quantity of water in the form of vapor will be more than 100 units. Thus, any minor fractional condensation of the vapor or collection of the fog could redissolve the trapper material and permit it to be entrained in the flow, thus being lost from the filter This mechanism has been proposed because in a number of experiments when there were two and, in some cases, three filters in series more material on the second filter than the first was found. This was not the case, however, in laboratory experiments with drift particles when the filters were operated without the fog and moist environment where the trapping efficiency was measured to be approximately 90%.

Still another undesirable factor in the behavior of the paper samplers was the fact that the quantity of material collected appeared to be consistently higher than the value determined by the PILLS system even when it was taken into account the fact that the PILLS system recorded only that part of the particle distribution function beyond, for example, 100μm. The inadequacy of extending this standard technique for dry particulate sampling to aerosols or large liquid particle sampling such as drift led us to consider other techniques or refinements. The application of standard cyclone techniques which operate by centrifugal separation was attempted. The results were slightly more encouraging

but still led to values larger than those determined by the PILLS system. One mechanism that would lead to the larger values in both cases would be field contamination. Another mechanism which would lead to more collected material is entrainment of liquid collected on the outside of the tube and drawn in to the inlet. In a cooling tower environment any metal or solid objects placed in the flow will literally be dripping with water.

To circumvent these difficulties, a new type isokinetic sampler was conceived and developed by Environmental Systems which circumvented by design some of these most important problems. The final design is shown in Figure 8 along with a newer design using glass wool fill material which has yet not been used in field situations. Its background levels for Mg and Ca are roughly three times that of the bead tube but its trapping efficiency should be higher. No tests on other background levels have been run.

The principles of the bead-filled tube are as follows. The resistance wire on the outside of the tube provides a heat input of 60-70 watts. The heat transfer slug forces the air to flow near the walls for more effective heat introduction to elevate the temperature of the air. The hot air in turn heats the bead column and other glass surfaces. The drift particles entering isokinetically then impinge upon the hot glass surfaces and evaporate to dryness leaving their material residue.

The advantages of this construction are that the sampling volume rate can be substantially higher than for the paper filter (I.D. = 25mm) and, more important, the glass tubes can be cleaned to have a much lower and more predictable background contribution.

The addition of the heat external to the tube provides two further improvements. First, it heats the air such that condensation cannot occur thereby defeating the mechanism for loss by re-dilution and re-entrainment of condensate within the tube. Second, the heat outside the tube prevents the condensate from forming on the tube and then being entrained in the flow. In operation in an actual cooling tower environment the tubes thus appear dry, both inside and outside, and feel warm to the touch even at the top of the tube.

A substantial number of performance experiments were run on these tubes in the laboratory and in the field. The trapping and holding efficiency of the tubes for the dried residue is typically better than 90%. More important, the tubes agree reasonably well with the integrated quantity of material predicted by the PILLS system when they are run simultaneously and under compatible conditions.

SENSITIVE PAPERS

A technique which has been widely used for measurement of particle size distributions external to cooling towers has been the sensitive paper

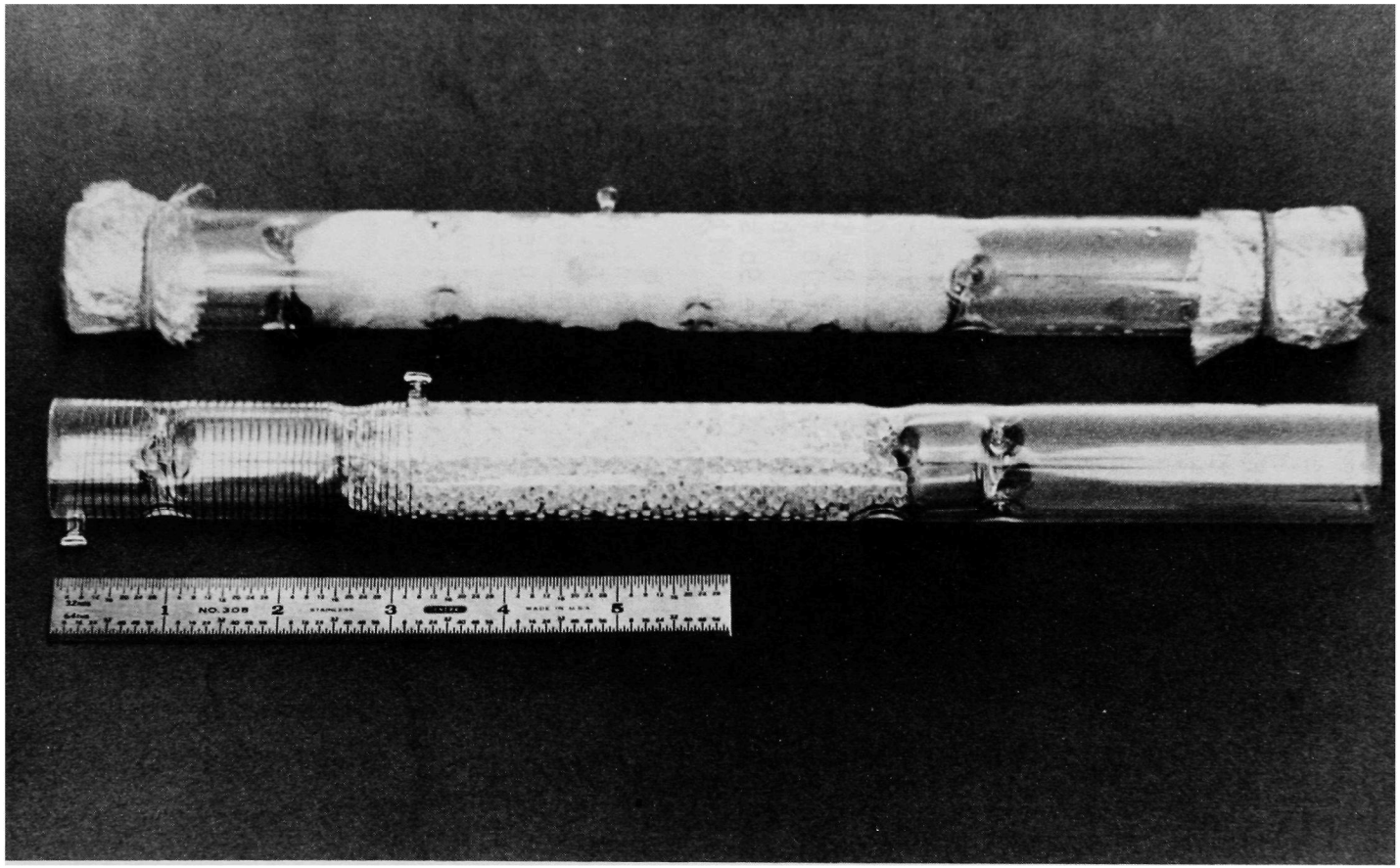


FIGURE 8
ISOKINETIC SAMPLER TUBES

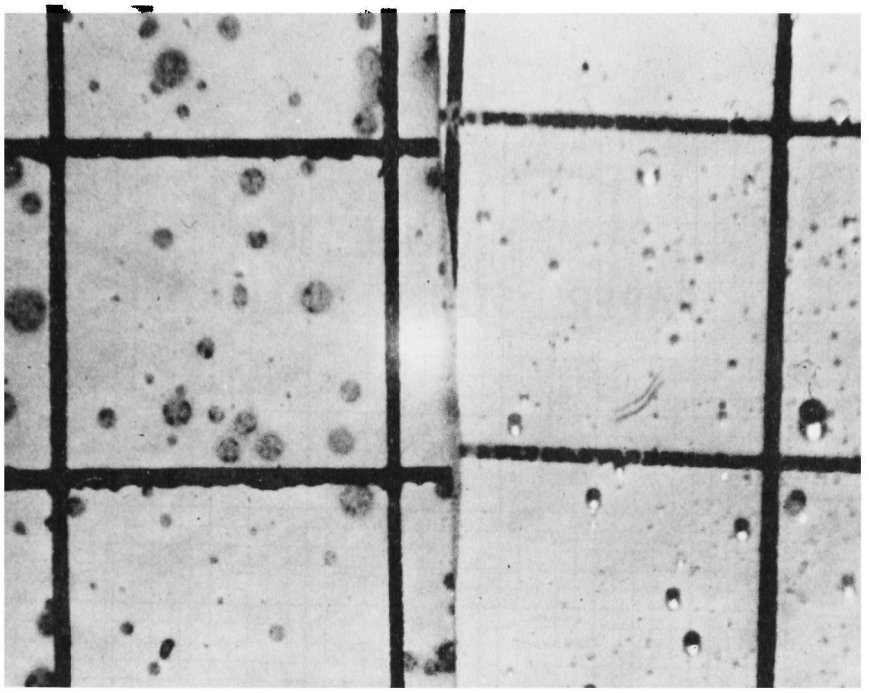
approach. According to Chilton (5), the standard preparation of the papers proceeds by soaking them in a 1% solution of potassium ferricyanide, allowing them to dry, and then dusting them liberally with finely ground ferrous ammonium sulfate. The papers thus prepared are pale yellow in color and when impinged by a liquid droplet form a blue stain which is clearly distinguishable on the yellow background and whose diameter is related to the diameter of the impinging particle. The paper itself is important. Considerable improvement resulted by using milli-pore membrane filter paper rather than the Whatman No. 1 paper used by Chilton. With the latter paper, the fibrous structure is so coarse as to obviate measuring particle stains which are smaller than 30 or 40um.

Figure 9a shows a photo-micrograph showing both the sensitized paper and a teflon sheet placed over a piece of the gridded paper upon which a spray from an atomizer has been applied. Figure 10 shows the calibration realized by the following technique. The spray aerosol sprayer produced a particle distribution on the teflon surface. A piece of the unexposed sensitized paper was then laid on top of the teflon sheet. Before the paper was placed over the distribution, a photo-micrograph was taken of the particle field. After the stains were made, the paper was turned over and another photo-micrograph was taken. By this means, a one to one correspondence between the original particle field and its inverted image on the sensitive papers was generated. These data are shown on the calibration curve of Figure 10. Figure 9b shows typical data which were collected at Oak Ridge for comparison with the isokinetic and PILLS system.

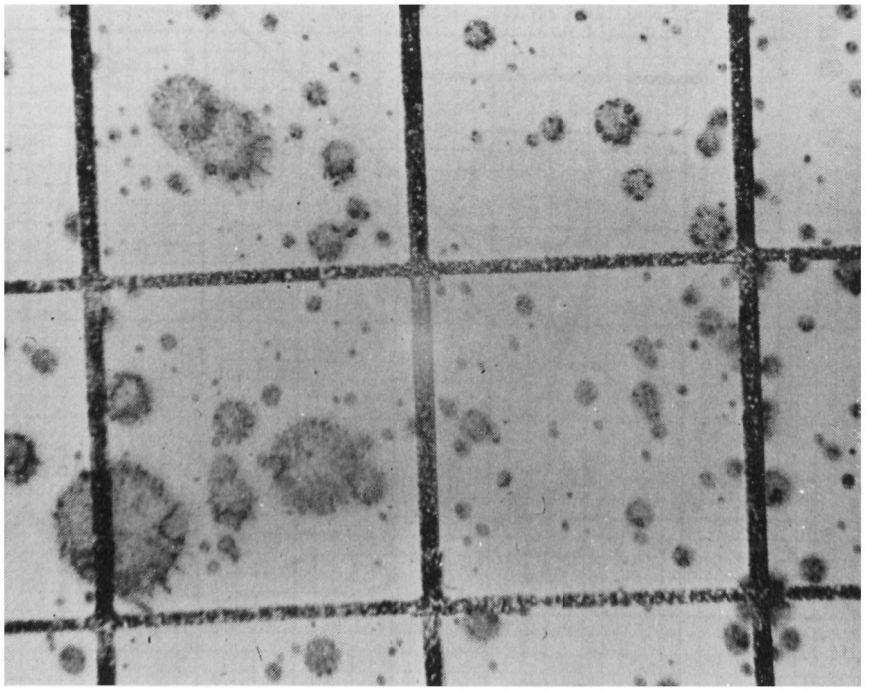
It should be noted that the sensitive paper measurement suffers from the fog background problem in much the same way that the PILLS system does. The large quantity of fog and any condensate from the even larger quantity of vapor produces an exposure of the sensitive paper precluding large exposure times. It can therefore be appreciated that the sensitive paper must be exposed for a brief period of time (typically 1-2 seconds) and consequently will provide less information about the large drift particles which occur far less frequently than small particles. In this sense the laser and the sensitive paper are complementary.

IN-LINE HOLOGRAPHY

It was mentioned earlier that two electro-optic techniques were considered at the outset. For completeness, a discussion of the feasibility demonstration of in-line holography using the gallium arsenide laser is included. To our knowledge, this effort produced the first instrumentation application of in-line infrared holography and the second hologram ever to be made with infrared laser light (6). Figure 11 shows schematically the typical in-line holographic recording and reconstruction arrangement. The principle of holographic recording is that light from the coherent source scattered by the particle interfers at the film plane with light which proceeds unscattered and forms the hologram interference pattern.



CALIBRATION



OAK RIDGE DATA

FIGURE 9 PAPER STAIN

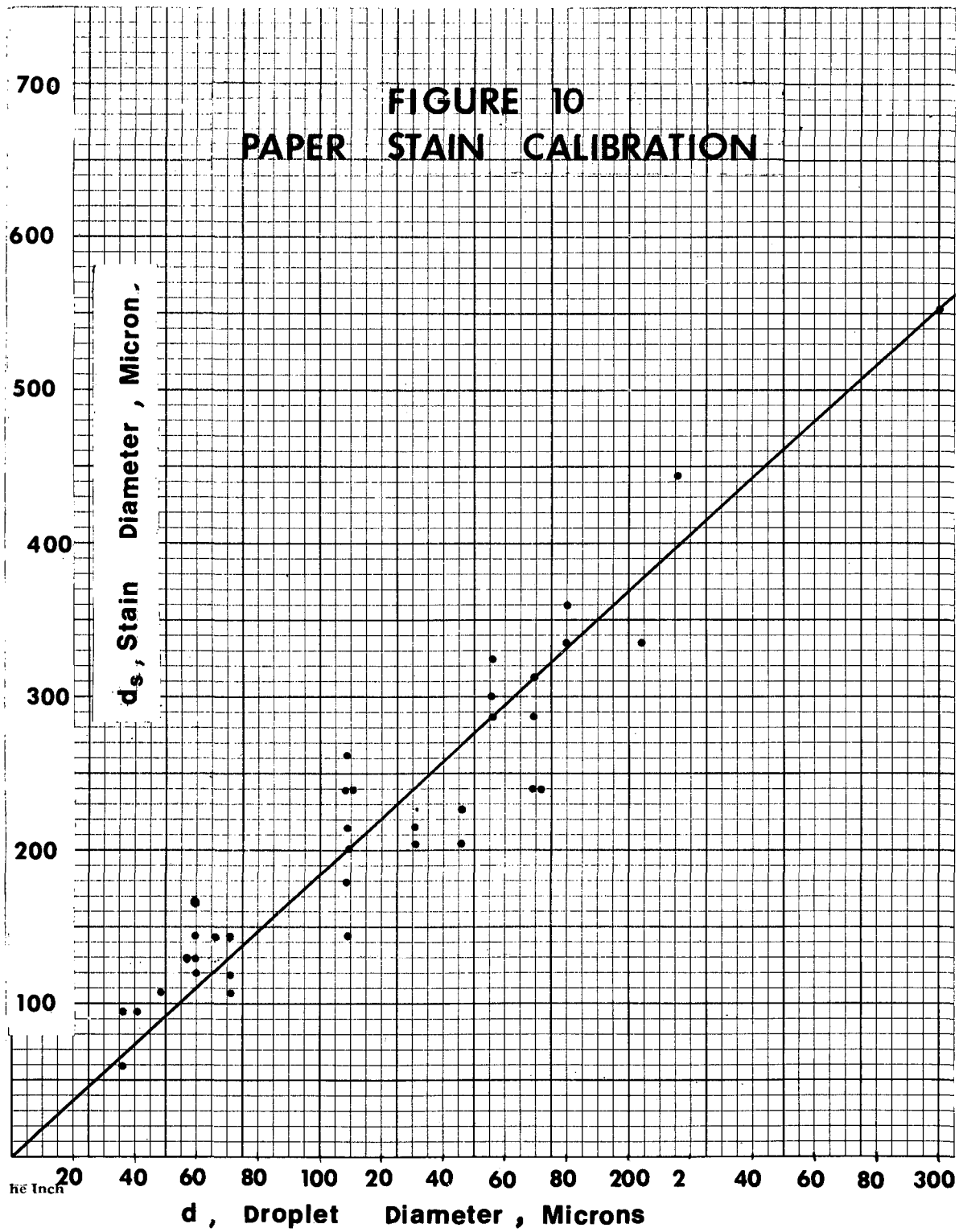


FIGURE 10
PAPER STAIN CALIBRATION
700
600
500
400
300
200
100
d_s, Stain Diameter, Micron
20
40
60
80
100
20
40
60
80
200
2
40
60
80
300
d, Droplet Diameter, Microns

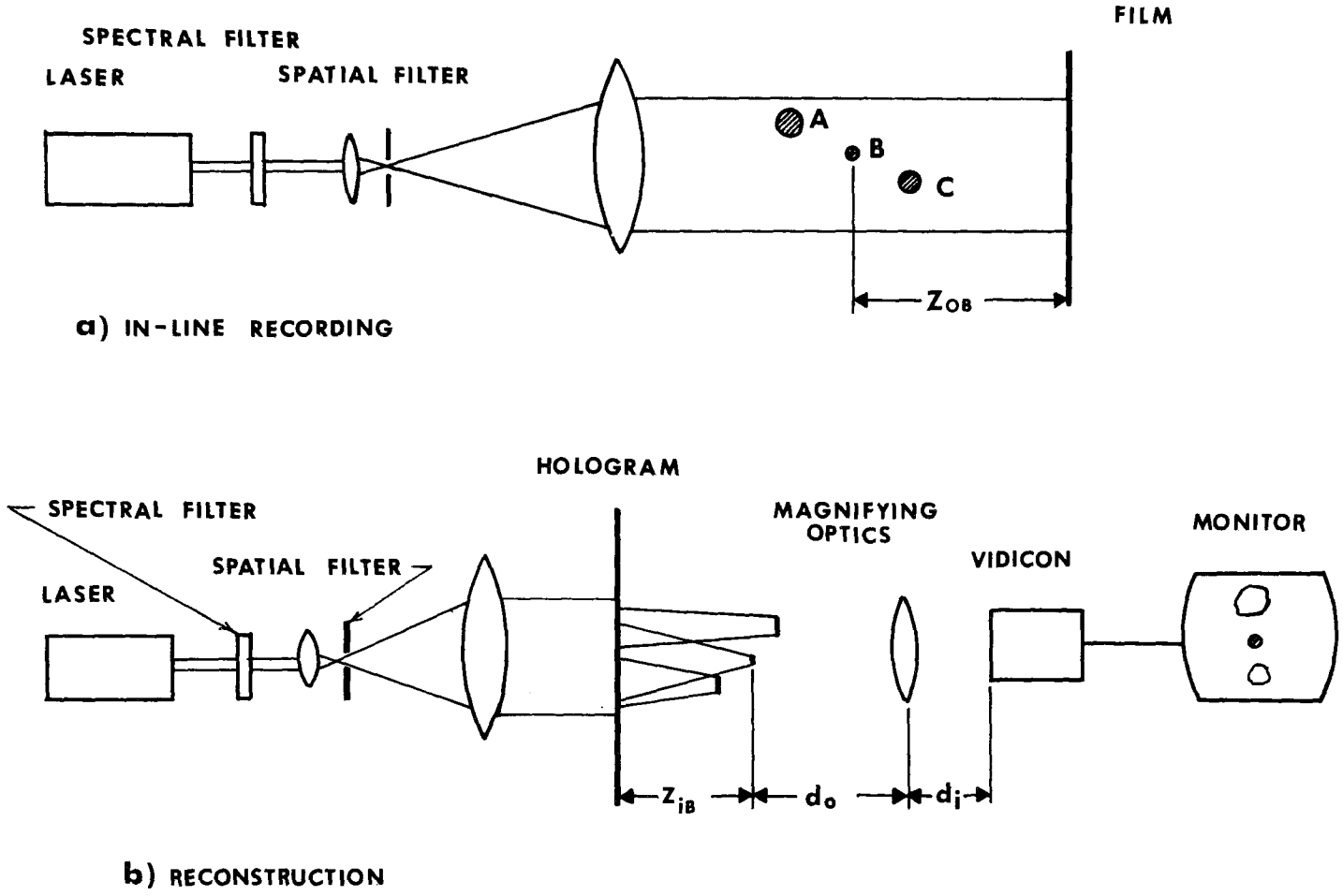


FIGURE 11

IN-LINE HOLOGRAPHY

It is also often callecd a Gabor hologram because this was the first type of hologram to be invented and was accomplished by Dennis Gabor in 1948. The photographic film, desirably of high spatial resolution, is then processed and replaced in the electromagnetic wave. The diffraction by the interference pattern density variations in the film is such as to produce, essentially, a focusing of light to produce a real image of the hologram of the particle as shown in Figure 11b. This can be viewed on a white, diffusely-reflecting card or, with considerable advantage, with a closed circuit television system. If the recording and reconstruction light waves have the same properties the reconstructed image will be at the same distance as the recording distance and the cross-section of the particles under reconstruction will be the same as the cross-sections of the original scattering particles. In this way, one may therefore map out a dynamic particle field with respect to both position and size distribution. This technique has been extended to provide the concept of holographic velocemetry as reported in Reference 7.

The holographic system has the advantages that the hologram may be recorded in the field and reconstructed in the calm, quiet environment of the laboratory and of providing a permanent record of the particle distribution. It has the disadvantages that the reconstruction necessitates a two-step process and is therefore lengthy. It also has the disadvantage that particles smaller than 50um are difficult to resolve, particularly in the presence of a large number of fog particles. It therefore suffers from the fog problem also. Its principle range would be the larger particles. But these occur less frequently, necessitating collection of many holograms.

Although determined not to be the best choice for drift instrumentation, it should be said in defense of the in-line, infrared holocamera whose feasibility we did demonstrate that the recording and reconstruction was realized on standard infrared film using standard processing techniques and the accuracy and ease of reconstruction of large particles with background was equivalent to that using visible lasers and associated techniques which have been practiced widely (6).

COMPARISON OF THE VARIOUS DRIFT INSTRUMENTATION SYSTEMS

It is worth summarizing the important points comparing the PILLS and other drift instrumentation systems to indicate their respective relative advantages as well as the complementary nature of the three field-proven systems.

The principle advantage of the PILLS system is its amenability to automatic data processing permitting it to be an essentially on-line measuring instrument. The disadvantage of the present single V_s system is that it is limited to measuring particles above a size which is determined by the quantity of fog present.

Isokinetic sampling is not capable of resolving particle size, but gives an integrated measure of the mass of material contained in unit volume of air flow. A significant advantage of this integrated measurement is that it gives, directly, data on the materials which may be regarded as providing the pollution or environmental impact.

The sensitive paper technique has the advantage of simplicity in data collection but the disadvantage of lengthy data reduction. It is sensitive also to fog and condensate which constitutes for it a background as for the PILLS system. It is important to recognize, however, that the limitation imposed by the fog on the PILLS system is to make it incapable of measuring small particles and applicable, therefore, to the larger particles whereas the limitation on the sensitive paper is just the converse. Thus for a complete drift measurement program it is conceivable to utilize all three of these techniques.

Holography is of limited value for recording small drift particles and requires a lengthy data reduction process.

Several other techniques which would measure small particles of water have been considered and/or proposed to us in the course of this study. Such techniques include electron beam scattering and a wide variety of impingement devices which leave a crater in some material which can be related through calibration to the diameter of the impinging particle. It is even conceivable that the isokinetic sampling can be made mass selective by utilizing centrifugal force effects. As drift continues to be a problem, it is certain that many other techniques will be proposed and realized. The presentation here was limited to those techniques for which we have actually demonstrated feasibility and used in the field.

SECTION VI

SUMMARY OF DRIFT MEASUREMENTS PERFORMED BY SEPTEMBER 1971

The results of several drift measurement experiments is now reported and include measurements on a small commercial cooling tower, two large mechanical draft towers, and brief data for a hyperbolic tower. The most complete data are given for the mechanical draft towers which were at Oak Ridge. The others are included for completeness and are with the permission of our clients for whom we ran these tests.

AQUATOWER

This small commercial unit (≈ 15 tons, circulation rate 45 gpm) was found to drift approximately .01%. It was from simultaneous isokinetic and PILLS measurements that the calibration factor for the PILLS system was determined as shown in the Appendix. Figure 12 gives the particle size distribution versus particle diameter. Here the data are reported as the number of particles per cubic foot per micron size range. The particle density per unit size range extends over two orders of magnitude in going from 80μm to over 300μm. Note the humps in the curve around 100μm and around 200μm. Figure 13 shows the mass distribution per cubic foot per unit size range which has a minimum in the neighborhood of 175um. It is important to observe that this curve is plotted against linear coordinates whereas the particle distribution is plotted logarithmically.

DOUBLE FLOW MECHANICAL DRAFT TOWER

Measurements were made on a commercial tower (fan diameter 28 feet, circulation rate 12,500 gpm, range 23°F, approach 7°F) when the PILLS system was in an early state of development. Procedurally, the system was traversed across the vertical efflux of the tower at the top of the fan cone and appropriate area segmentations were generated to realize a numerical integration for the total drift in grams per second leaving the tower. The area segmentation and the integrated drift yield associated with a given area are shown in Figure 14. Station No. 2 was obviously a "hot spot" for drift emission and led to a substantial portion of the total drift emission. Visual observations indicated that this hot spot was rather localized and a better representation would have been realized had several diameters scans been made.

In this early stage of development the dynamic range of the PILLS system provided only a factor of about 4:1 in particle size. The upper and lower points could, however, be adjusted. Figure 15 shows the mass emission histogram versus particle size and exhibits a distinct minimum in the neighborhood of 110μm. Without the advantage of having reduced

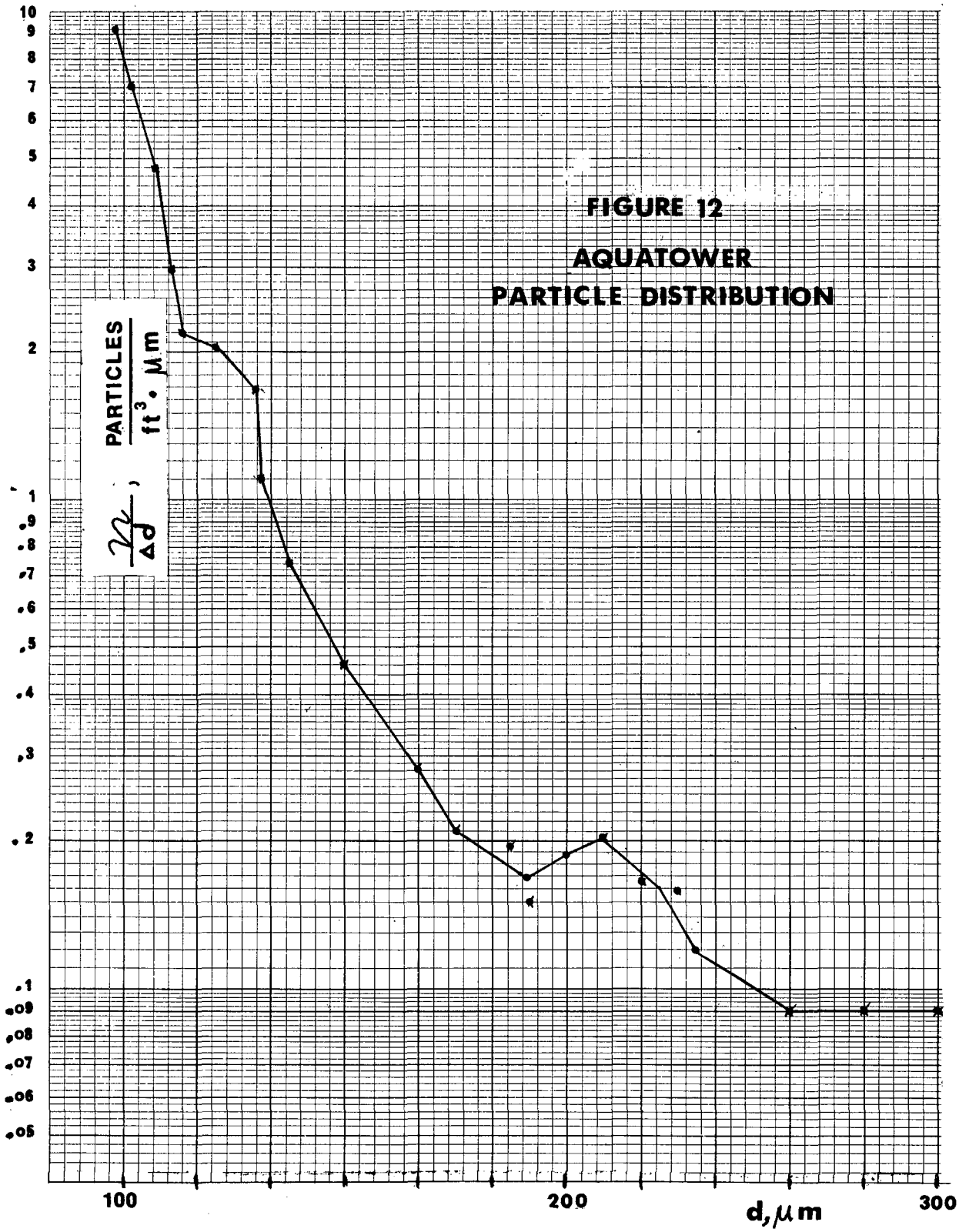
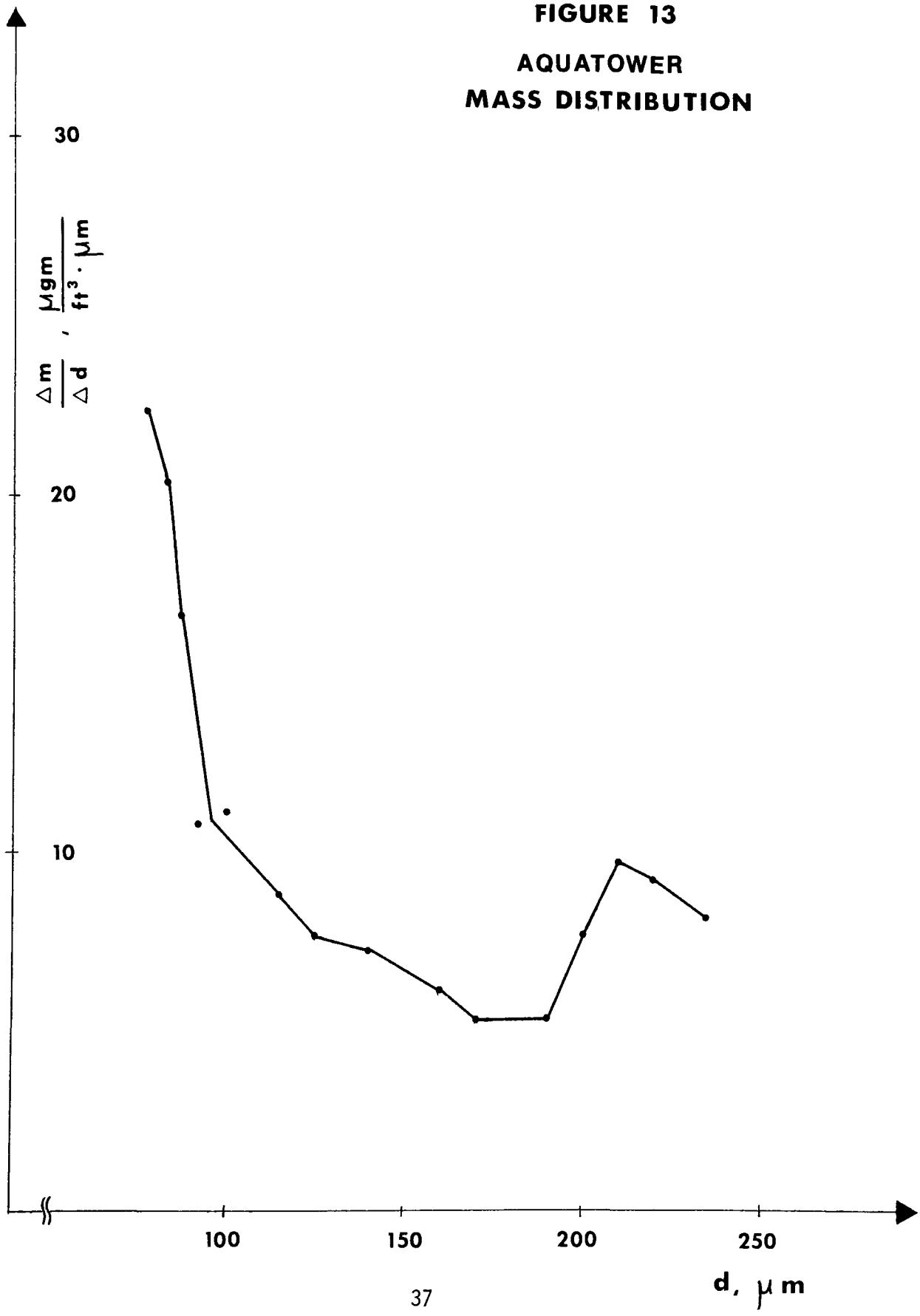
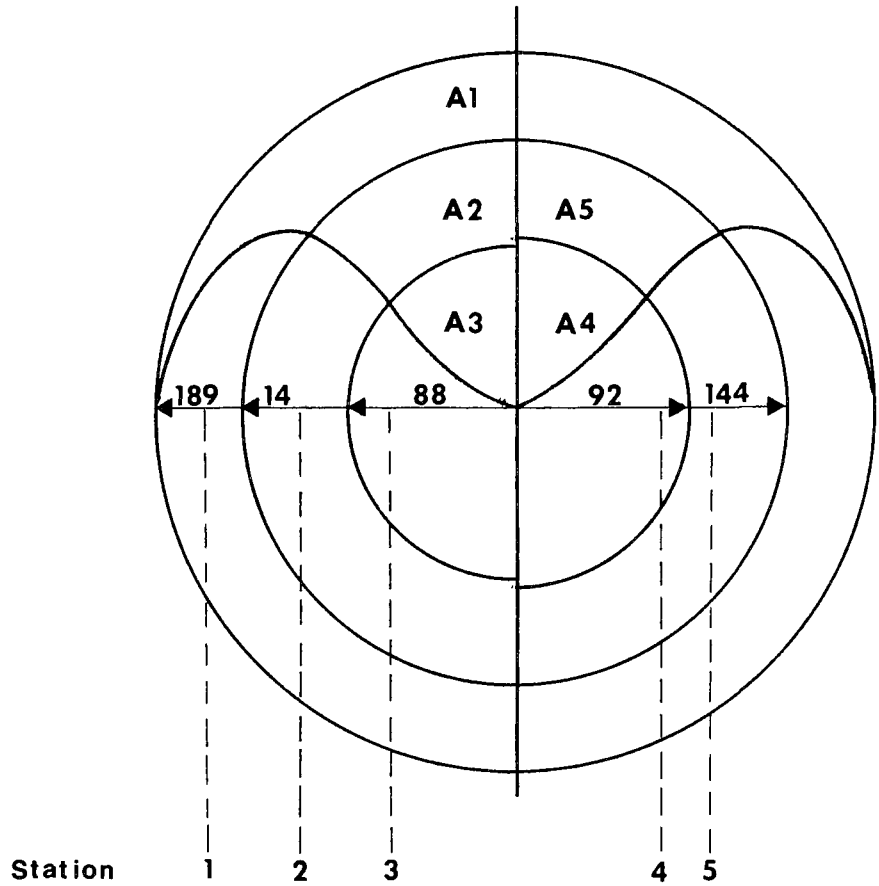


FIGURE 12
AQUATOWER
PARTICLE DISTRIBUTION
$\frac{\Delta N}{\Delta d}$, $\frac{\text{PARTICLES}}{\text{ft}^3 \cdot \mu\text{m}}$
10
9
8
7
6
5
4
3
2
1
.9
.8
.7
.6
.5
.4
.3
.2
.1
.09
.08
.07
.06
.05
100
200
300
d, μm

FIGURE 13

AQUATOWER
MASS DISTRIBUTION





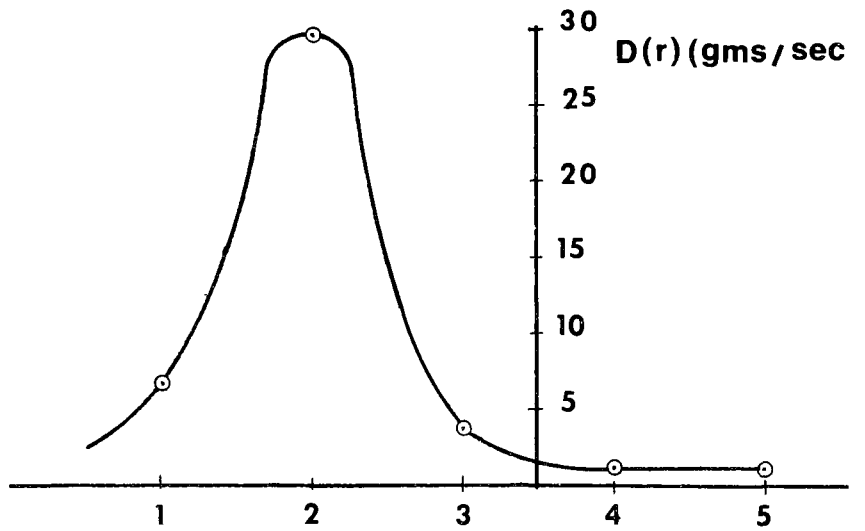


FIGURE 14

TOWER SEGMENTATION AND DRIFT RESULT

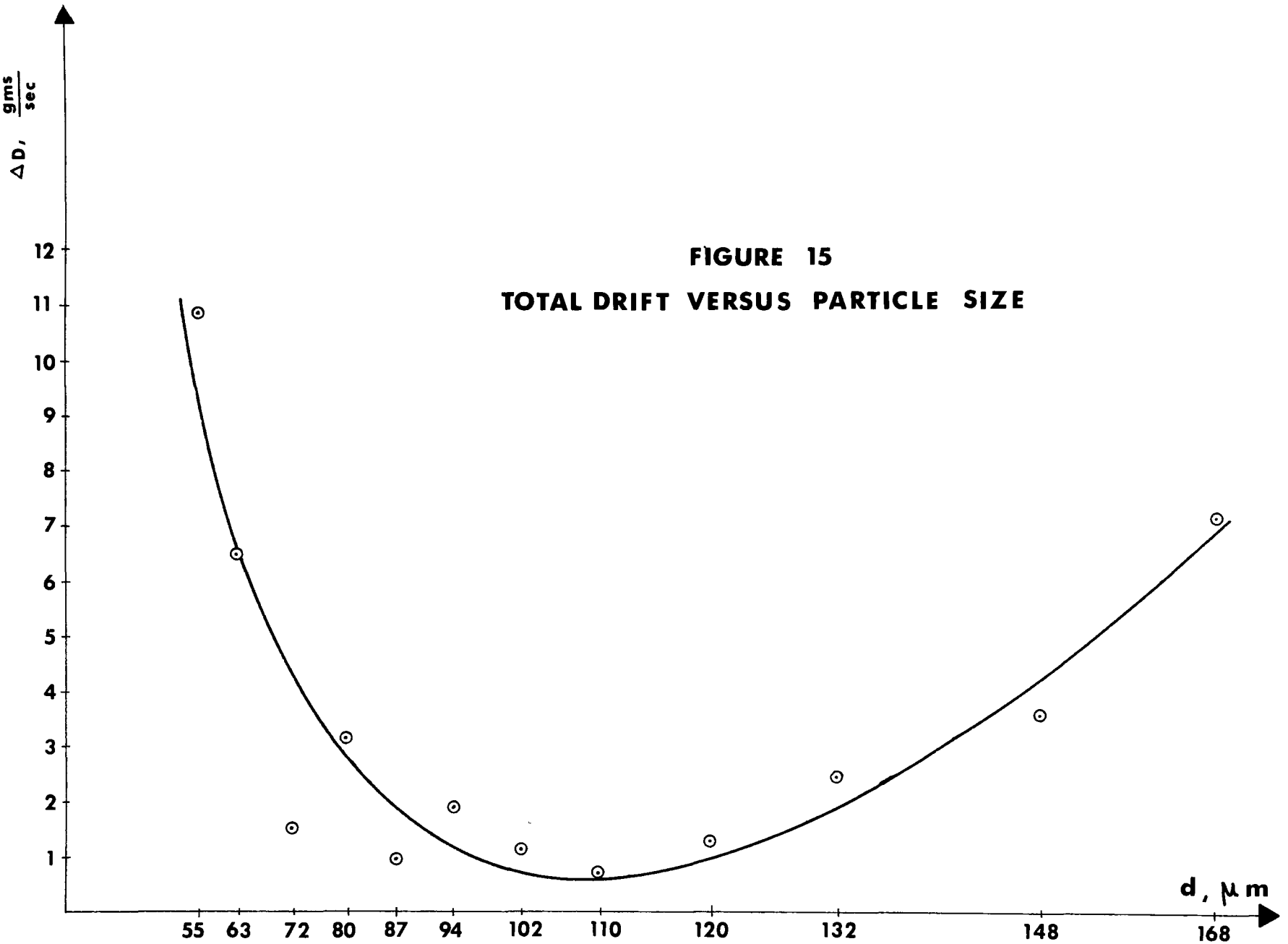


FIGURE 15

TOTAL DRIFT VERSUS PARTICLE SIZE

data, a field decision was made which resulted in the choice for the range of particle diameters shown. Data reduction indicated the surprising minimum. It is now conjectured that the basis for the minimum - which occurred for every station - is that the components below 100μm constitute drift which has passed through the drift eliminators and the components above 100μm evidence a secondary generation and/or transmission mechanism. A secondary generation mechanism might be described as "tearing-off" at leading and trailing edges of the drift eliminator and other structural members. It is interesting to note that the Aquatower data taken when the instrument was in a more refined state of development as shown in Figure 13 also show a minimum but in the vicinity of 175μm. Note that both towers had a horizontal velocity component in the fill whereas the large mechanical draft tower had a final vertical component.

OAK RIDGE MECHANICAL DRAFT TOWER

The most comprehensive drift measurements were made at Oak Ridge involving the PILLS system, the isokinetic sampler system, and the sensitive paper techniques. Significant design parameters are: fan diameter 18 feet, circulation rate 6,050 gpm, range 10°F, approach 7°F. (The circulation rate was 4,000 gpm during the drift measurements.) The PILLS and isokinetic system data are recorded simultaneously and the isokinetic sampling head was immediately above the scattering volume V_S as shown in Figure 3 such as to make them simultaneously observe the same particle distribution at the same point in space.

The principles for each of the measurement techniques have been given earlier and the data in Table 1 are presented for brevity. Figure 16 presents graphically the essential data.

Procedurally, we first determined the velocity profile with a vane anemometer mounted on the same carriage which was used subsequently for the PILLS and isokinetic system traverse. The velocity profile is shown as the dashed curve in Figure 16. An area segmentation as shown in Figure 16 was realized to accomplish the approximate numerical integration for drift. Visual observations indicated a high degree of uniformity for the drift around the tower. Further, the night on which these measurements were made had very low wind conditions. A single diameter traverse was thus adequate. The fourth column in Table 1 indicates the total number of cubic feet collected at each of the stations. It was not possible with the pump available to realize isokinetic conditions at Stations 2 and 6 and velocities were utilized which were approximately 30% lower than isokinetic. The fifth and sixth columns in the table give the amount of water determined by two analyses on both magnesium and calcium. The seventh column gives the mean for these values. The eighth, ninth, and tenth columns give the drift per unit area, that is the grams per second per square foot, as determined by the three techniques. The isokinetic results are determined according to the formula shown on the table. It was assumed that the trapping efficiency of the glass bead tubes was 100%.

TABLE 1

OAK RIDGE COOLING TOWER DATA SUMMARY

Station j	V_j ft/sec	A_j ft^2	V_{kj} ft^3	M_{Mg} gms	M_{Ca} gms	M gms	gms/sec ft^2 D/A/IK	D/A/PILLS	D/A/Paper	gms/sec D_j/IK	D_j/PILLS
1	20	27.5	356	.52	.50	.51	.029	.012, d>80μm		.79	.33
2	35	64.4	354	1.54	.87	1.21	.119	.047, d>120		7.67	3.03
3	18.3	38.5	252	.30	.38	.34	.025	.017, d>100		.95	.65
5	18.3	38.5	259	.34	.41	.37	.026	.0046, d>80		1.01	.18
6	34.2	64.4	264	.95	.63	.79	.10	.13, d>140u	.16	6.55	8.36
7	29	27.5	237	.65	.56	.61	.074	.037, d>120		2.04	1.02

$$D = \sum_j D_j = 19 \qquad 13.6 \text{ gm/sec}$$

$C_{tr}|\,Mg = 24.5$ ppm

$C_{tr}|\,Ca = 160$ ppm

$$M = \frac{M_{tr}}{C_{tr}}$$

$$\frac{D_j}{A} = \frac{V_j M_j}{T V_k}$$

$$R = 4000 \text{ gpm} = 25 \times 10^4 \text{ gm/sec}$$

$$\text{drift percentage} = \delta = \begin{cases} \dfrac{19 \times 100\%}{25 \times 10^4} = 0.0076\%, \text{ IK} \\[2ex] \dfrac{13.6 \times 100\%}{25 \times 10^4} = 0.0055\%, \text{ PILLS} \end{cases}$$

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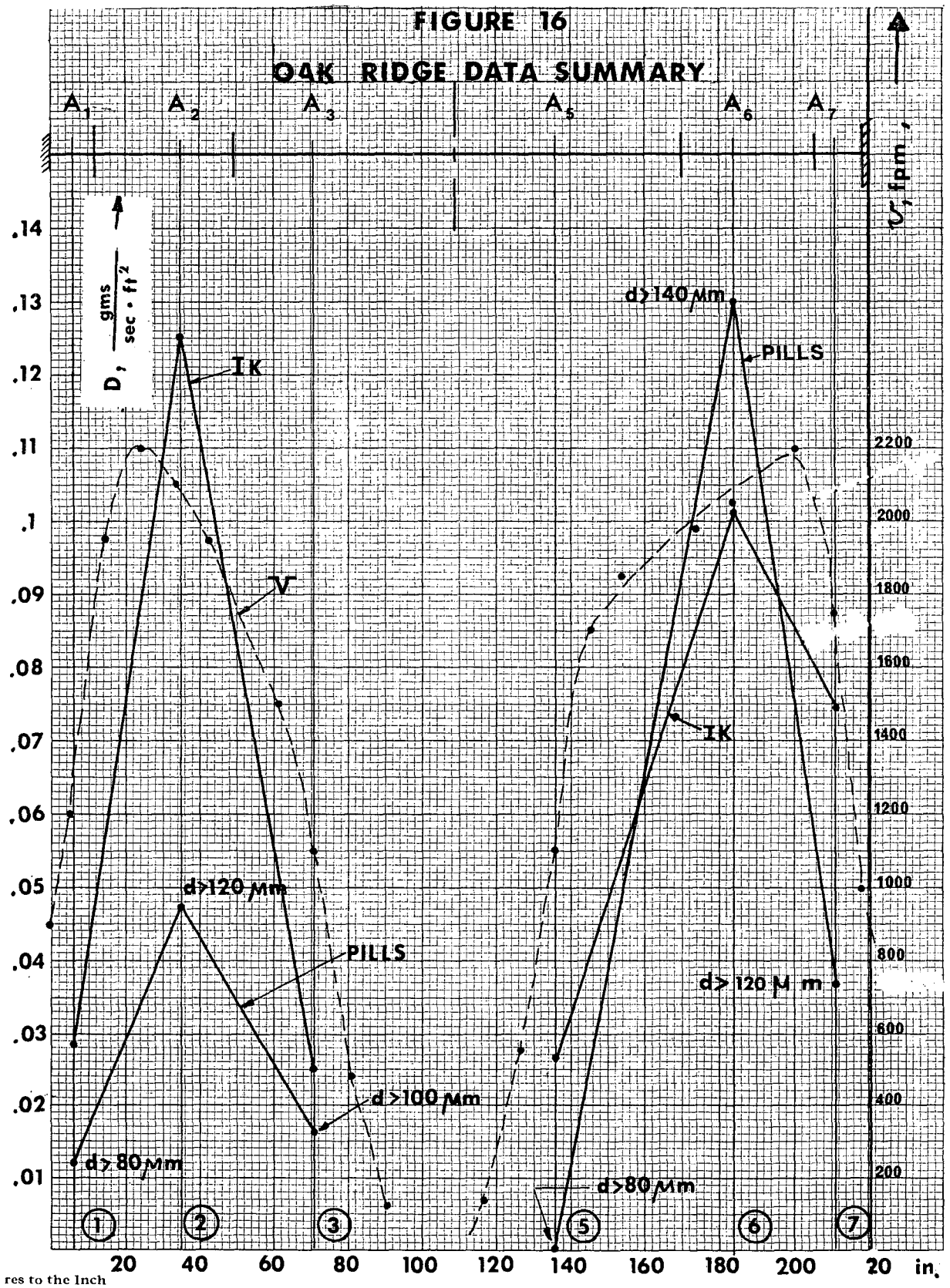


res to the Inch

Note particularly the qualification on particle diameter in colume nine giving the determination based on the PILLS system. For example, d > 80μm means that the mass was measured by the PILLS system for all particles larger than 80μm at Station 1. At all stations except 1 and 5, it turned out that the counting rate was too rapid for the visual-CRO technique described in Section IV. In order to reduce the counting rate to within the capability of the observers it was necessary to increase the lower level cutoff. For Station 6 this was 140μm and therefore a substantial amount of material at this point was not counted. The availability of either a digital counter or, better, a pulse height analyzer system would have obviated this difficulty and it would have been possible to record the drift down to the approximate 80μm limit under the meteorological conditions under which the drift was made since fog was not a severe problem. In other measurements made both earlier and later, the fog yield was higher and provided a higher cutoff value.

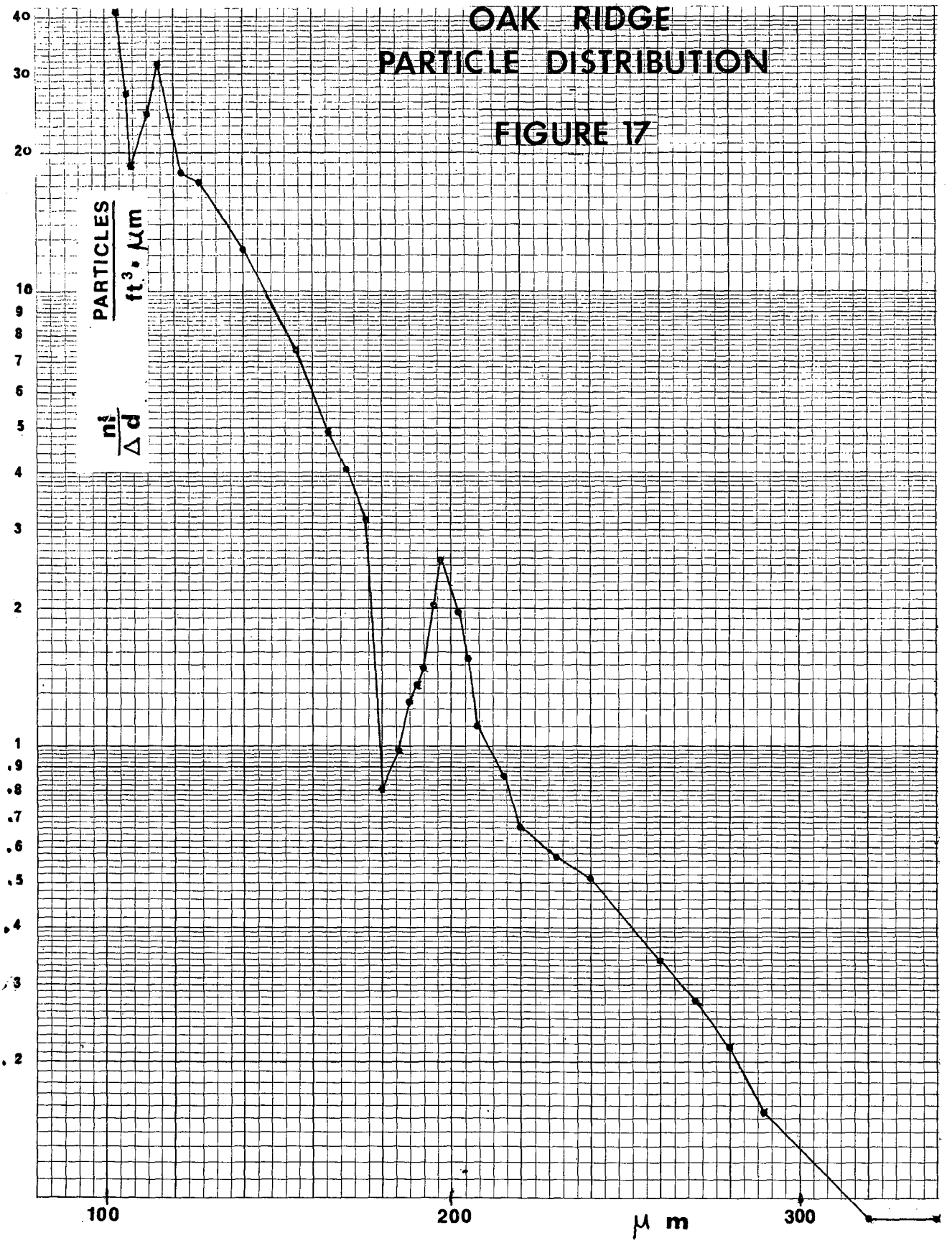
Figure 16 summarizes these data for the individual stations. The straight line connecting points for the data are for clarity of presentation and do not indicate the drift emission profile. Some comparison of the PILLS and IK curves is in order. First, in every case except at Station 6 the isokinetic data are larger than the PILLS data, which is as it should be since the isokinetic data includes all particles and the PILLS data includes all particles beyond a given diameter. At Station 6 the drift was sufficiently large that the heat input to the hot bead sampler was inadequate to keep the tube hot which could possibly have led to a reduced trapping efficiency. At Station 2 the sampling velocity was lower than isokinetic. Consequently, the actual drift is lower than that shown. When the sampling velocity is lower than isokinetic there is a tendency to record more drift.

Columns 11 and 12 give the integrated drift water emission as determined via the PILLS and IK techniques using the velocity profile and the area segmentation shown in Figure 16. The total tower emission is shown at the bottom of the respective columns.

The general agreement in all these data must be regarded at this point as encouraging.

Figure 17 shows the particle size histogram and again it is to be noted that it spans more than two orders of magnitude and shows the presence of minor variations in the vicinity of approximately 110μm and approximately 190μm. Figure 18 shows on a linear scale the mass histogram or distribution and we again note the minor peaks as also evident on the particle histogram. Note that there are particles larger than 300μm being emitted.

Figure 19 indicates the results made for paper stain measurements made at one station on the identical unit immediately adjacent to the unit on which the measurements using the PILLS and isokinetic systems was made. The presentation is in the form of a block type histogram with


OAK RIDGE
PARTICLE DISTRIBUTION
FIGURE 17
$\frac{n_i}{\Delta d}$ $\frac{\text{PARTICLES}}{ft^3 \cdot \mu m}$
40
30
20
10
9
8
7
6
5
4
3
2
1
.9
.8
.7
.6
.5
.4
.3
.2
100
200
300
μ m

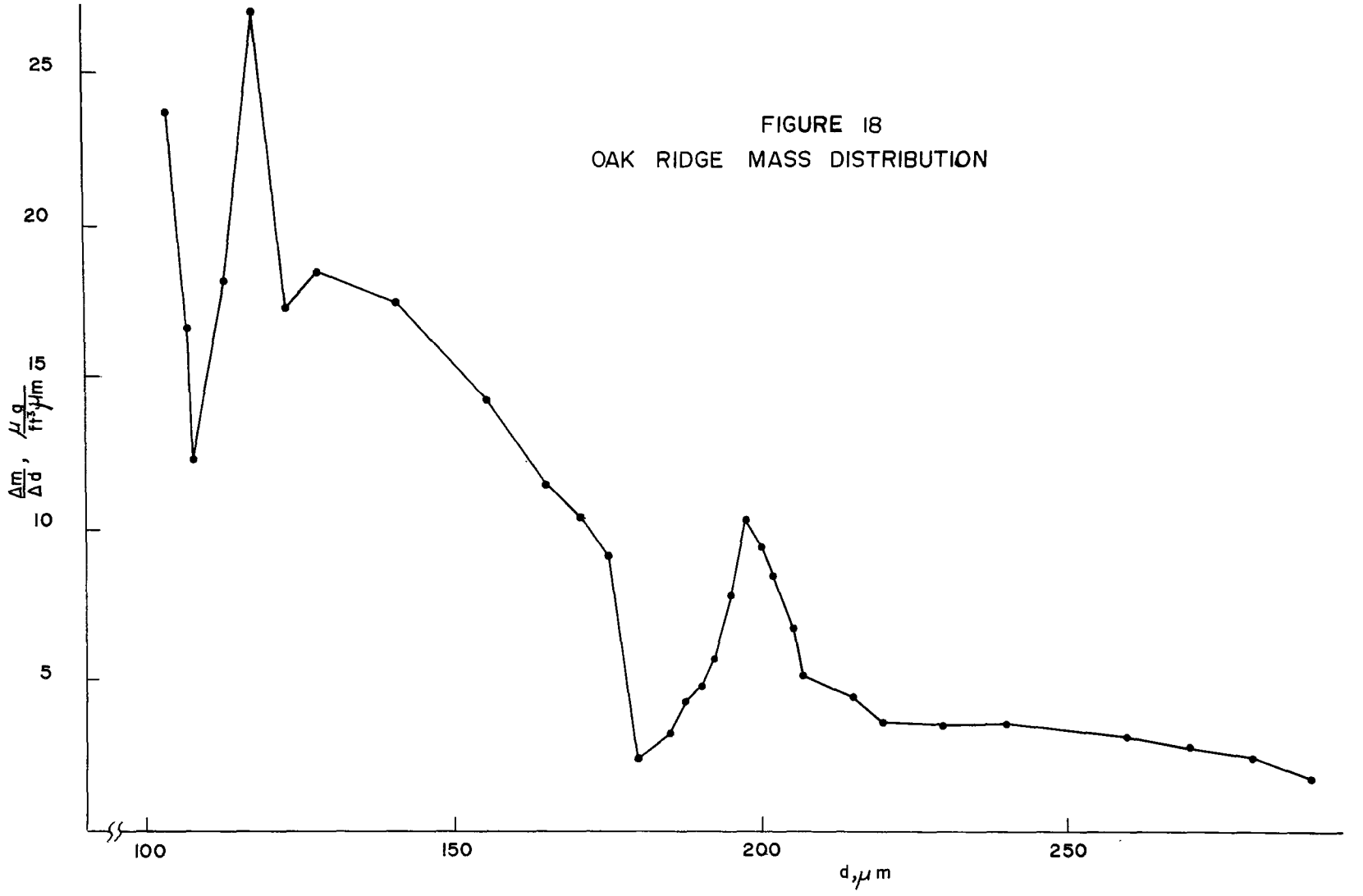


FIGURE 18
OAK RIDGE MASS DISTRIBUTION

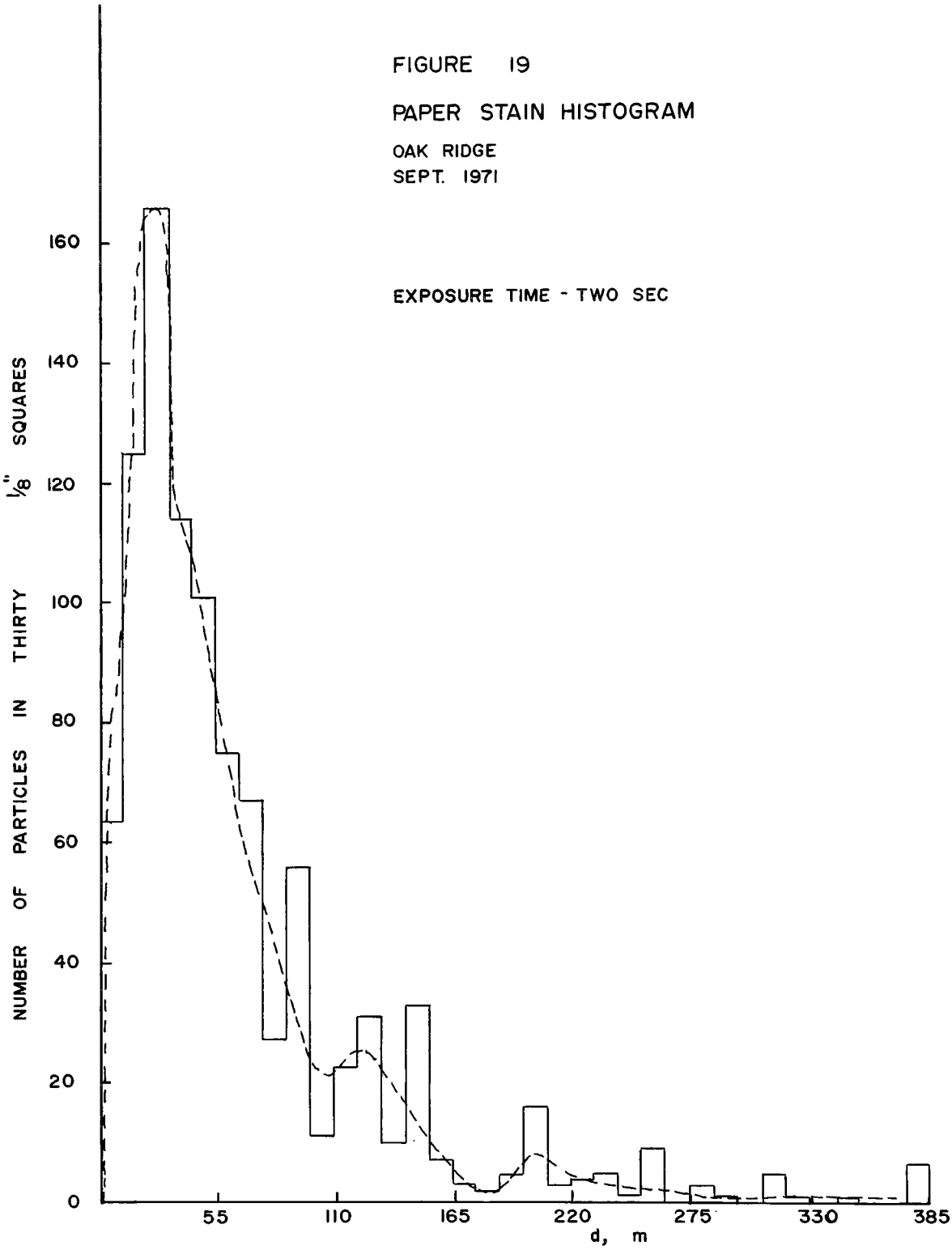


FIGURE 19
PAPER STAIN HISTOGRAM
OAK RIDGE
SEPT. 1971
EXPOSURE TIME - TWO SEC
NUMBER OF PARTICLES IN THIRTY 1/8" SQUARES
0
20
40
60
80
100
120
140
160
55
110
165
220
275
330
385
d, m

llum increments. For the first time we saw the particle distribution tend toward 0 below 100μm. This was possible because the fog was light when these data were taken and therefore did not constitute a severe background problem. Careful examination of the data permit drawing the dotted line shown in Figure 19 which again suggests that there are two minor peaks in the particle distribution. The result is regarded as highly encouraging giving as it does a check on the calibration of the PILLS system in demonstrating the existence of these two peaks.

That the mass emission of the small particles is negligible is verified by a rough estimate of the integrated mass as follows:

0 - 100μm ,	814 particles with $\bar{d}$ = 50μ,	53 x 10^{-6}
100 - 200μm ,	176 particles with $\bar{d}$ = 150,	311
200 - 300μm ,	49 particles with $\bar{d}$ = 250,	400
300um and up,	12 particles with $\bar{d}$ = 350,	269
		1,033 x 10^{-6} gms

Thus the 0-100μm size range contributes only about 5% to the mass emission.

A final rough but very interesting calculation based on the paper stain data is to note that the particle identified above were counted on thirty 1/8 x 1/8" squares and that the sampling time was approximately two seconds. This leads to an approximate value of

$$D/A = \frac{1{,}033 \text{ gms}}{30 \times (1/8)^2 \times (1/12)^2 \text{ft}^2 \times 2 \text{ secs}} = 0.16 \frac{\text{gms}}{\text{ft}^2\text{sec}}$$

whose agreement with the PILLS and IK values in a similar position on the other cell is also regarded as encouraging.

NATURAL DRAFT COOLING TOWER MEASUREMENTS

The PILLS and isokinetic systems developed by means of this contract have been applied to a large natural draft cooling tower. It is possible at this time to release the following data as shown in Table 2 which also summarizes the data from the other cooling tower observations. A drift percentage of 0.005% as determined via IK measurements is regarded as a representative number for state-of-the-art hyperbolic cooling towers having efficient and intact drift eliminators. It is to be noted that the PILLS system determined a drift percentage of 0.0012% for particles larger than 145μm in the vicinity of an inherent but minor void in the drift eliminator structure. Far greater levels were found in the vicinity of major voids. (These measurements were made within 6-10 feet of the drift eliminator surface.)

TABLE 2

SUMMARY: COOLING TOWER OBSERVATIONS

I.	AQUATOWER	(1) $\delta \approx .01\%$	IK	Two Whatman #1 filters, no heat load
		(2) ------	PILLS	Significant Mass > 250 μm
II.	MECHANICAL DRAFT (Oak Ridge)	(1) $\delta \approx .0076\%$	IK	Hot Beads
		(2) $\delta \gtrsim .0055\%$	PILLS	Count Rate Too Fast[1] for Small Particles
III.	MECHANICAL DRAFT	(1) $\delta \gtrsim .005\%$	PILLS	55-168 μm Distinct minimum; secondary mechanism
IV.	HYPERBOLIC	(1) $\delta \approx .005\%$	IK	Substantial Variations[2]
		(2) $\delta \gtrsim .0012\%$	PILLS	d > 145 μm, minor void
		(3) --------	PILLS	Few Particles with d > 100 μm in normal areas
		(4) $\epsilon > 99\%$	PILLS	d > 150 μm (ratio to case 2; ϵ = drift elimination efficiency)

[1] Visual counting of oscilloscope sweeps.

[2] Both in position and in time.

Probably as important as the 0.005% number, the PILLS system yielded as a result of a scan across a normal and intact portion of the drift eliminator structure that very few particles larger than a 100μm are present. It is suggested that the major components of drift in such a hyperbolic are to be found in the particle size range 50-150μm. Larger particles will be eliminated by the drift eliminators and smaller particles are unlikely to be generated unless a greater degree of atomization is employed.

Item IV also introduces the interesting concept of drift eliminator efficiency. PILLS measurements were made on the "up-wind" side of the drift eliminator structure and it was found that the quantity of water presented to the drift eliminator structure is at least two orders of magnitude larger than the quantity which goes through. (See Figure 5b for typical "up-wind" data.)

It must be stressed that these measurements were made inside the cooling tower near the drift eliminator face. The environmental conditions for equipment and personnel must be reported as extraordinarily hostile and unsafe. Fog was a severe problem. The variations in the significant parameters of interest, drift, air velocity, and temperature, are substantial in both space and time and these must be considered when generating a number representative of the total tower performance.

SECTION VII

ACKNOWLEDGEMENTS

Realizing the results herein reported has brought us into contact with many individuals in widely spaced disciplines. It is important to cite those who have been most instrumental but it is not possible to thank all.

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The cooperation of the Atomic Energy Commission in permitting the "shake-down" tests and final demonstration at the Oak Ridge National Laboratory permitted the work to be performed more conveniently and effectively. The administrative assistance of Dr. J.L. Liverman, ORNL Associate Director for Biomedical and Environmental Sciences, and Mr. M.M. Yarosh, Environmental Quality Program was beneficial. Convenient access to the cooling tower facilities and efficient and pleasant working conditions wer provided by Mr. B.B. Smith, Maintenance Supervisor.

Much of the basic information for this development was gathered by private communication, chiefly in the form of laboratory visits and extensive telephone conversations. Most helpful were Mr. R. Berglund and Dr. B. Liu, University of Minnesota, Mr. W. Kochmond, Cornell Aeronautical Labs, Dr. R. Nutt, ORTEC, and Mr. J. Keathley, ORNL. In addition to interesting technical discussions, Dr. Nutt and Mr. Keathley loaned us several specialized instruments for exploratory development and for the September 28 demonstration. Mr. J. Eddlemon, PULCIR, Inc., also provided equipment for these purposes.

We are grateful to Mr. R.A. Burns of General Public Utilities for permission to release the natural draft cooling tower data and to The Marley Company for permission to release data on the other large mechanical draft unit.

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Frederick M. Shofner
Technical Director

Carl O. Thomas
President

SECTION VIII

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SECTION IX

APPENDIX

MATHEMATICS OF PILLS CALIBRATION DETERMINATION VIA ISOKINETIC MEASUREMENTS

The calibration constant K of Equation 2 can be determined by recording a voltage histogram with the PILLS instrument and taking isokinetic sampling data of the same particle distribution. For accuracy, it is advantageous to sample a distribution similar to that expected in the field at the same position and at the same time. Both PILLS and isokinetic sampling can measure the same basic quantity, the mass of drift water per unit volume m.

By isokinetic sampling a mass of a certain ℓ^{th} mineral M_ℓ is collected from a sampling volume V_k. Thus the mass of drift water per unit volume is

$$m = \frac{M}{V_k} = \frac{M_\ell}{C_\ell V_k} \qquad \text{(A-1)}$$

where M is the mass of drift water and C_ℓ is the mineral concentration in the circulating water. It is assumed that the ℓth mineral concentration in the drift and the circulating water are the same.

With the PILLS instrument one resolves the particle distribution and obtains a voltage histogram. Let $f(v_i)$ be the count rate of particles with a size yielding a voltage v_i within an implied incremental range v_i. The number of the same size particles per volume is

$$n_i = f(v_i)\frac{\Delta t}{V_s} \qquad \text{(A-2)}$$

as has been derived in Equation 3. The water content per unit volume comprised of particles of this size is written as

$$\Delta m_i = s n_i \frac{\pi}{6} d_i^3$$

$$= s\ f(v_i)\frac{\Delta t}{V_s}\frac{\pi}{6} d_i^3$$

$$= s\ f(v_i)\ \frac{\Delta t}{V_s}\ \frac{\pi}{6}\ \frac{v_i}{K}^{3/2} \qquad \text{(A-2)}$$

The total water mass is the sum of the masses attributed by the individual particle sizes:

$$m = \sum_i s\ f(v_i)\ \frac{v_i^{3/2}}{K^{3/2}}\ \frac{\Delta t}{V_s}\ \frac{\pi}{6} \qquad \text{(A-3)}$$

Equating (A-1) and (A-3) gives

$$m = \frac{M_\ell}{C_\ell V_k} = \frac{s\Delta t}{V_s K^{3/2}}\ \frac{\pi}{6} \sum_i f(v_i) v_i^{3/2}$$

Since all parameters except k are known or measureable, the calibration constant is determined as a function of simultaneous isokinetic sampling and laser data:

$$k = \left[\frac{C_\ell}{M_\ell}\ \frac{V_k}{V_s}\ \frac{s\Delta t\pi}{6} \sum_i f(v_i) v_i^{3/2} \right]^{2/3} \qquad \text{(A-4)}$$

The calibration factor K was determined using the Aquatower operating with no heat load, thereby permitting measurements down the instrument noise limit (≈80 μm for this configuration). Finally, even though the isokinetic collection includes the drift particles below the noise limit, their exclusion by the PILLS system makes negligible difference in the value of K because their mass is a small fraction of the total emission.

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LOW-LEVEL DRIFT INSTRUMENTATION

10 Author(s)

Shofner, Frederick M.
Thomas, Carl O.

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25 Identifiers (Starred First)

*Cooling Tower Drift Instrumentation

27 Abstract

Instrumentation for measurement of low level drift from cooling towers was developed. Emphasis was placed on the Particulate Instrumentation by Laser Light Scattering (PILLS) System.which is capable of on-line measurement and, with incorporation of existing pulse height analyzer and mini-computer equipment, complete on-line data reduction. Complementary techniques of isokinetic sampling and sensitive paper sampling were developed and field proven. Feasibility was demonstrated for an infrared in-line holocamera system. The design principles and engineering trade-offs for the PILLS, IK, and sensitive paper techniques are described. Drift performance data are given for a small air conditioning cooling tower unit, two large mechanical draft cooling towers, and a natural draft tower.

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