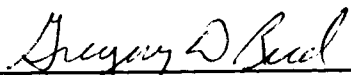
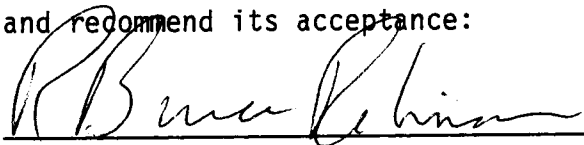
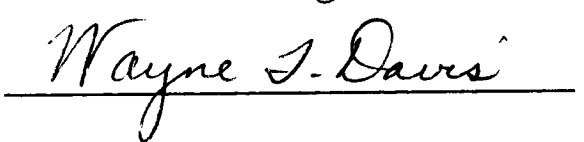


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PARTICLE SIZE DISTRIBUTION IN THE
CLARIFICATION PROCESS

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Patricia del Carmen Mery
March 1985

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ABSTRACT

A study of particle size distribution was performed in order to predict the clarifying performance in the water clarification process.

A series of jar-tests were run using raw water from the Mark B. Whitaker Water Treatment Plant, Knoxville, Tennessee, and an alum coagulant. Dosages from 10 to 35 mg/l were tested.

Observations of the flocs were made using a 35 mm camera with a macro lens. The flocs were measured by projecting the negatives on a large screen. A HIAC/ROYCO Model 4100 was used to measure floc particles smaller than 75 μm .

A computer program was developed to calculate the dimensionless concentration $C(t)/C(0)$ at time t . The program requires as inputs the ranges of particle size and the number of particles in each range. Assuming spherical particles, uniform initial distribution, same floc density, and settling in a quiescent system, the program calculates the settling velocity of each set of particles and the particle concentration at different settling times.

The optimum dosage was determined by a comparison of turbidity-time and concentration-time curves. The first curve was obtained by direct measurement of the parameters during the jar-tests, and the second curve was obtained using the computer program fed with the data obtained photographically and with the particle counter.

The evidence from this research clearly indicates that the initial floc particle size distribution is one of the principal determinants of coagulant dosage control of the clarification process. So the knowledge of this parameter gives us a quick and better way of determining coagulant dosage.

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CHAPTER I

INTRODUCTION

The most common method for removing colloidal matter from water is by coagulating and flocculating it with a hydrolyzing metal coagulant followed by sedimentation and filtration. Salts of aluminum (Al(III)) and iron (Fe(III)) are the most widely used coagulants.

The objective of coagulation is the removal of colloidal turbidity, color, bacteria, viruses, algae, and organic debris, by producing a floc of such size and density that the major portion will settle out in the allowed settling time. The remaining turbidity will be removed by the filter.

Several investigators [1-4] have referred to size distribution of floc particles, floc volume concentration and floc density as important floc characteristics in flocculation and settling. Coagulation has been studied by several techniques such as the jar-test, floc density, settled floc volume concentration, membrane filtration, conductivity, zeta potential, electronic particle counting, and pilot plant operation among others. Most of these techniques give a limited amount of information.

Many water-treatment specialists [5-12] use laboratory jar-test information as a design criteria of plant operation and plant design. Their work has provided increased insights into the mechanisms of mixing, coagulation and flocculation, and sedimentation. However,

the major disadvantages of the jar-test are time and interpretation of the results. The jar-test cannot be analyzed fast enough to keep pace with changes in the raw-water when rivers make rapid, erratic changes. Another major criticism of the jar-test technique is the small scale of the model. A jar tester cannot be assumed to be a true hydraulic model of a large prototype basin. The two devices are not geometrically similar, so the size of the floc particles cannot be exactly analyzed according to the principles of similitude.

The purpose of this study was to test a simple and fast technique to determine the economic amount of coagulant based on the floc particle size distribution and the resultant settling characteristics.

CHAPTER II

THEORY

Impurities in water occur in widely varying sizes. Table 2-1 gives the sizes of materials commonly involved in water treatment.

Table 2-1. Sizes of Materials Involved in Water Treatment.

Material	Particle Diameter (μm)
Sand	500
Soil	1-100
Bacteria	0.3-3.0
Viruses	0.005-0.01
Floc Particles	100-2000

The removal of a large portion of these impurities is accomplished by sedimentation. However, colloids, discrete particles with extremely small size (0.0001-0.000001 mm diameter) will not settle in a reasonable time. To remove these particles by gravitational settling it is necessary first to aggregate them into larger particles called flocs.

Colloidal particles remain in suspension because of surface properties which prevent particles from approaching each other.

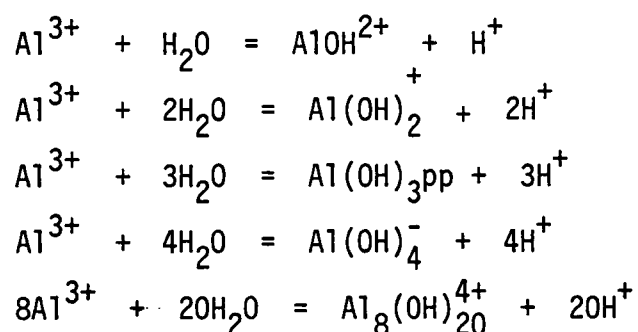
Theories of colloidal stability distinguish between two types of colloids, hydrophillic and hydrophobic. Hydrophillic colloids have a strong affinity for water. They isolate themselves from inter-particle contact by surrounding their surface with a layer of water molecules by a process called hydration. On the other hand hydrophobic colloids have little tendency to become wetted. These particles owe their stability to the electrical charge they possess. Hydrophobic particles surround themselves by an electrical double layer consisting of the charged particle and a cover of ions of opposite charge from the water solution.

Removing colloidal particles from water can be accomplished by particle transport to permit interparticle contact and by particle destabilization to permit the agglomeration of them when the contact is produced. Weber [13] used the term coagulation for the overall process and flocculation only for the transport process.

Depending on the chemical coagulant the destabilization of colloids may be accomplished in different ways. Stumm and O'Melia [14], after examing the adsorption of coagulants on colloids present in water and based on chemical considerations, concluded that: "Coagulation is a time-dependent process including several reaction steps: (1) hydrolysis of multivalent metal ions and subsequent polymerization to multinuclear hydrolysis species; (2) adsorption of hydrolysis species at the solid-solution interface to accomplish destabilization of the colloid; (3) aggregation of destabilized particles by interparticle bridging involving particle transport and chemical interactions; (4) aggregation of destabilized particles by particle transport and

Van der Waals forces; (5) "aging" of flocs, accompanied by chemical changes in the structure of Me-OH-Me linkages, concurrent change in floc sorbability and in the extent of floc hydration; and (6) precipitation of the metal hydroxide." The authors also stated that some of these steps occur sequentially, some overlap (steps 1 and 2), and some may occur concurrently under certain conditions (steps 3 and 4, or step 6 with steps 1-5).

The mechanics of destabilization by addition of alum to water has been studied by several investigators [14-16]. Figure 2-1 shows possible reactions for alum. Aluminum sulfate dissolves in water releasing SO_4^{-2} ions to solution. The aquometal ion $\text{Al}(\text{H}_2\text{O})_2^+$ is acidic; it is a proton donor, thus alkalinity is consumed. A few typical reactions follow:



Considering the solubility of Al(III) in water as a function of pH, Figure 2-2 shows that the minimum solubility occurs near pH 6.0. The shaded area shows the Al(III) concentration-pH range often observed in water treatment practice. Alum dosages between 5 to 100 mg/l and pH from 6 to 8.

Schematic curves of residual turbidity versus alum dose are shown in Figure 2-3. Each of these curves is subdivided into four

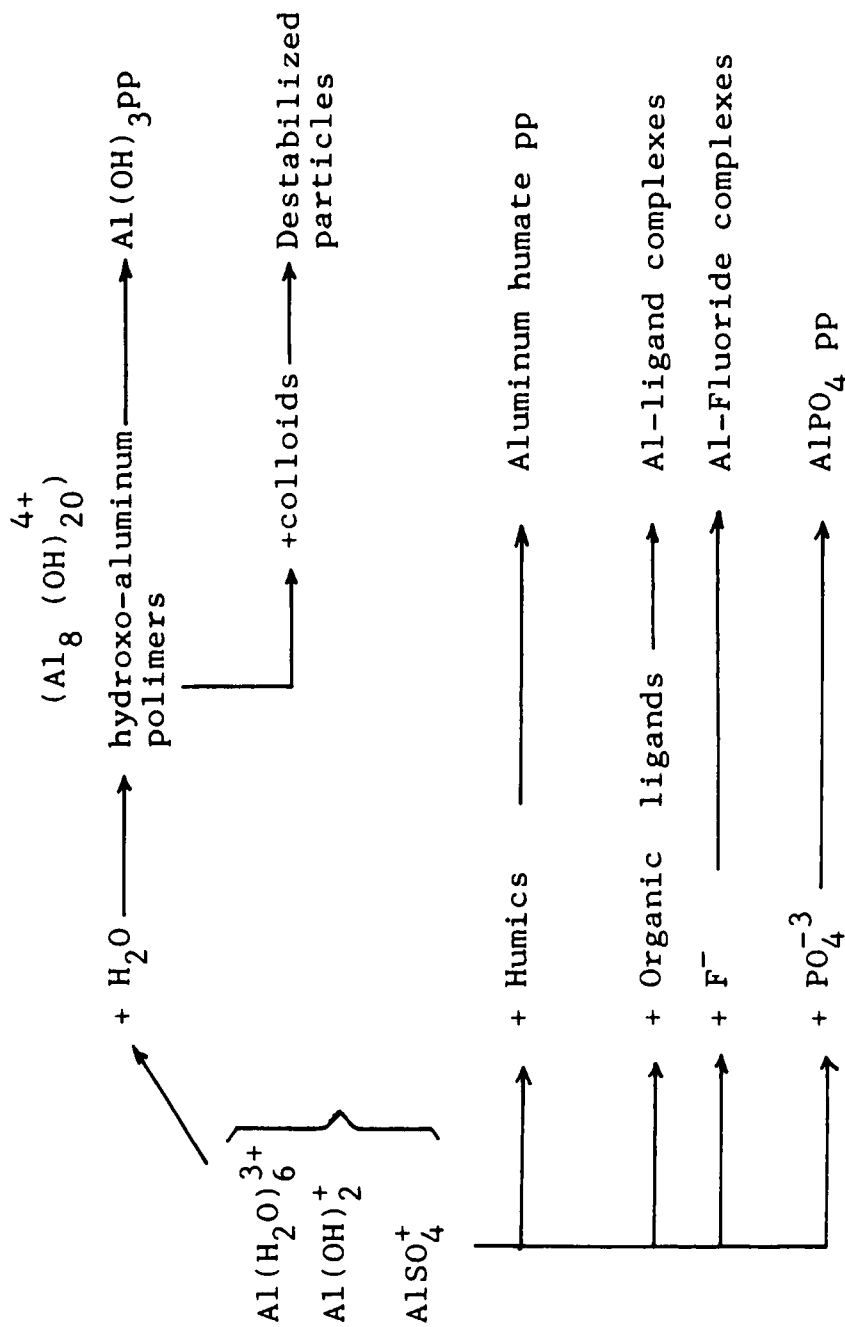


Figure 2-1. Possible Reaction for Al(III).

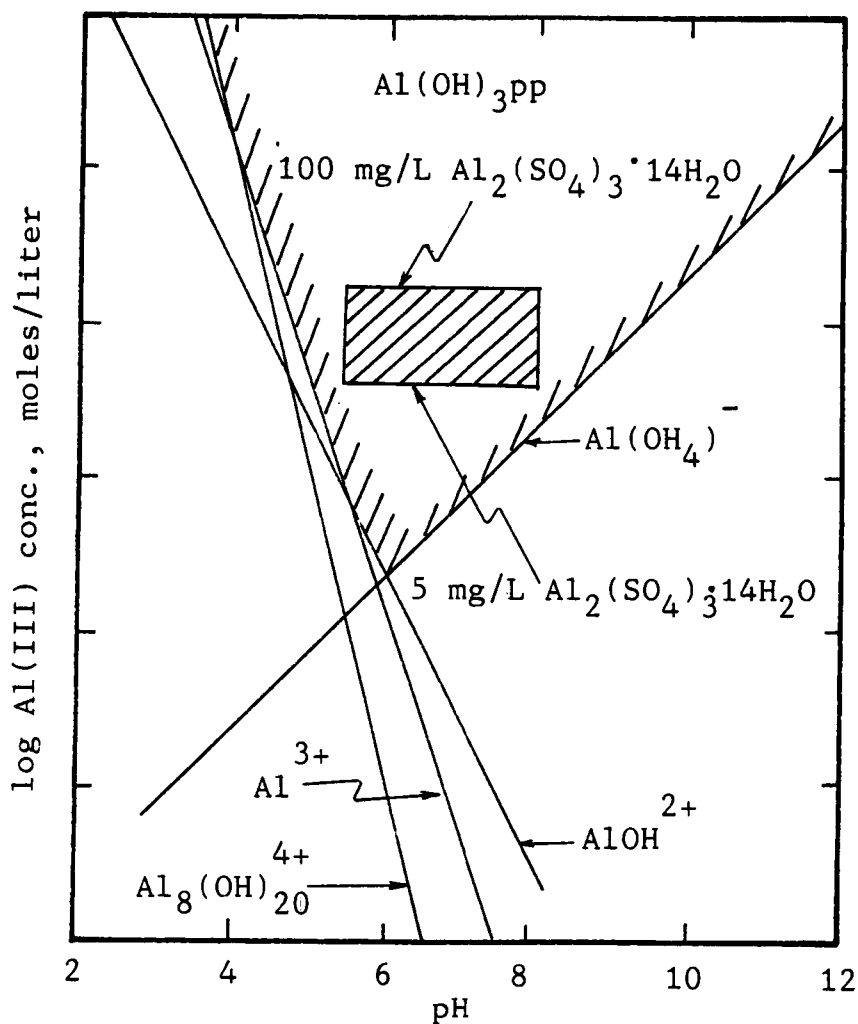


Figure 2-2. Solubility of $\text{Al}(\text{OH})_3\text{pp}$ in Water.
(Shaded area is the concentration-pH range often used for alum in water treatment.)

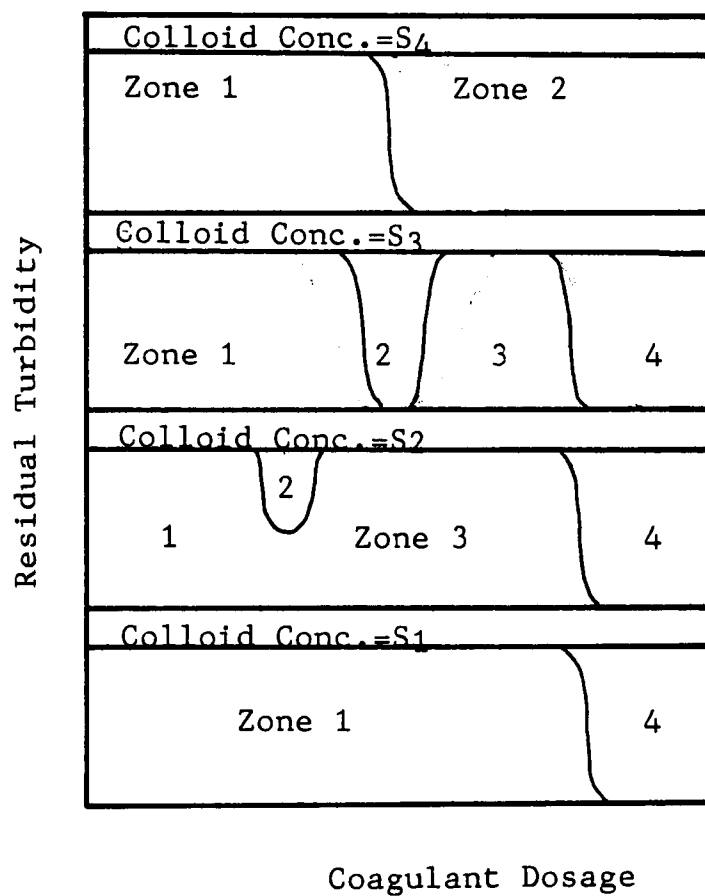


Figure 2-3. Schematic Representation of Coagulation Observed in Jar-Test Using $Al(III)$ at Constant pH.
From: Weber, W. J. Physicochemical process.

zones. In zone 1, at low alum doses there is no reduction in turbidity. There is insufficient Al(III) to provide effective destabilization. In zone 2 an increase in alum dose produces destabilization and permits particle aggregation. In zone 3 a further addition of alum will produce restabilization of the particles because the aluminum hydrolysis products almost completely cover the particle. In zone 4 an increase of alum to very high doses results in the formation of a precipitate of Al(OH) pp . This precipitate enmeshes colloidal particles in it and settles rapidly. This method of coagulation is often called "sweep floc." Presumably sweep floc is a large floc with consistently good settling characteristics. Usually water treatment plants operate in the sweep range so they can manage changing influent conditions.

The interparticle contacts to produce the growth of the flocs can be accomplished in several ways: (1) thermal motion; (2) fluid motion; and (3) differential settling. See Figure 2-4. For submicron particles the growth of these flocs is induced by Brownian motion, that brings the particles in contact with each other. This process is called perikinetic flocculation. This mechanism slows down when the floc particles grow to a size of about 1 micron and when the number of colloid particles decreases. Since 1-micron particles do not settle well, particle collisions must be induced by fluid motion. This process is called orthokinetic flocculation. The particles continue to grow until they reach a limiting size. According to several investigators, the particle size is inversely proportional to the velocity gradient, G . The velocity gradient is defined by Camp [10-12] as:

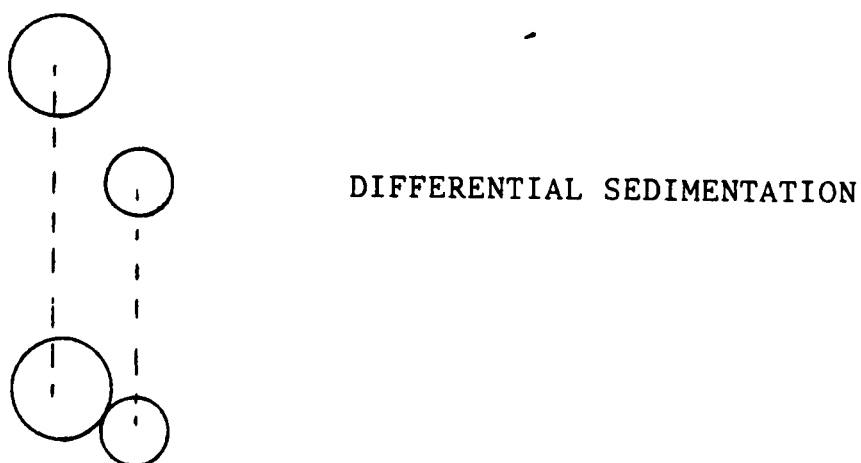
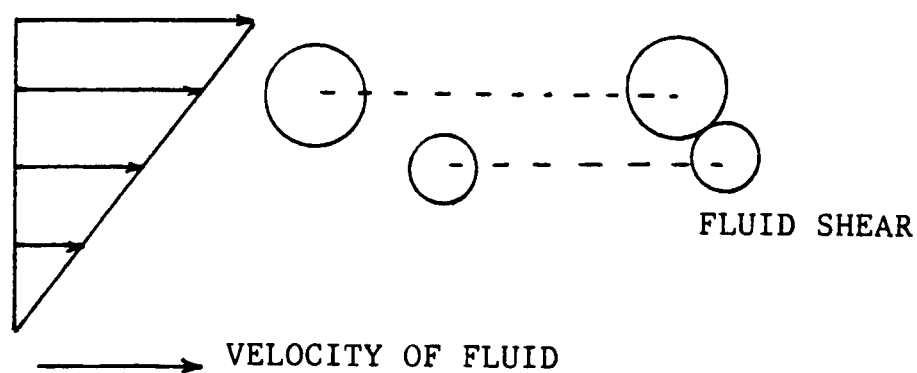
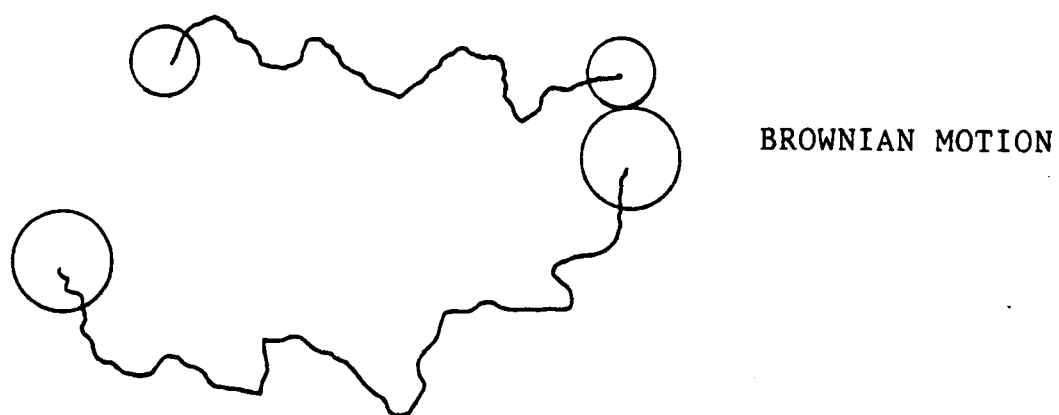


Figure 2-4. Mechanisms of Particle Transport and Interparticle Collisions.

$$G = \sqrt{W/\mu}$$

in which W is the dissipation function or power input per unit of volume of liquid and μ the absolute viscosity of the fluid. While this definition of G is not totally accurate, it is a simple indicator which can be used to show relative changes in mixing intensity.

The viscosity of the fluid is proportional to the shearing stress τ and the velocity gradient at a given point (G'):

$$\tau = \mu G'$$

It is obvious that as velocity gradient increases, shear stress also increases. As floc particles grow in size they become weaker and more easily torn apart. So, in general, one can state that to form small floc particles relatively high velocity gradients are required, and to form large floc particles relatively low velocity gradients may be used.

Differential settling refers to the contact process in which the rapidly settling particles overtake and collide with smaller particles that are settling at a slower rate. It has been emphasized that homogeneous suspensions of colloidal particles can not be flocculated by this process. When the particles are all the same size the range of collision between them is zero. All particles have the same settling velocity and there is no differential settling.

The relative importance of the three mechanisms of interparticle contact can be visualized in Figure 2-5. This figure was obtained from Hunt, who adapted an analysis by Friedlander [17], and is a comparison

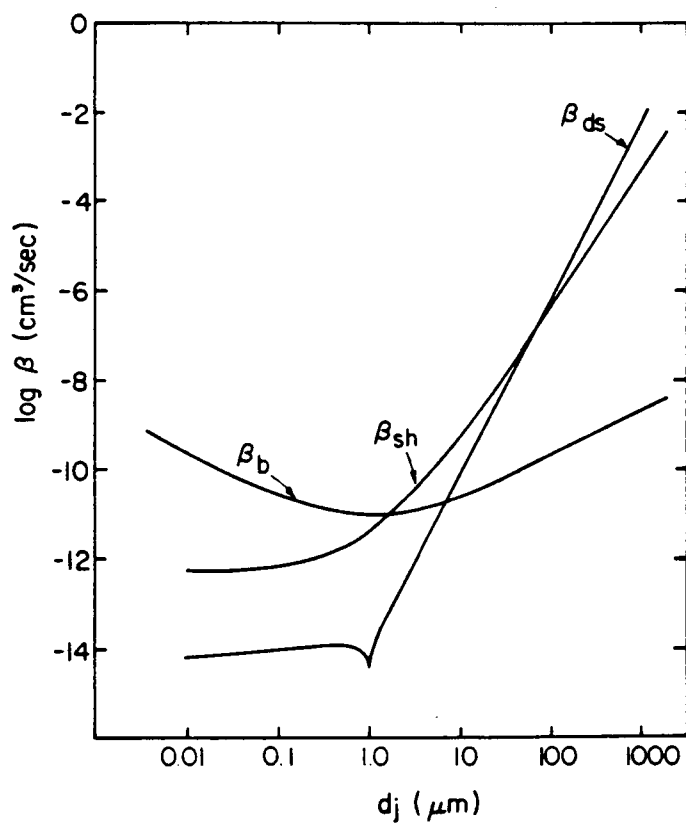


Figure 2-5. Comparison of the Collision Functions for Brownian, Shear, and Differential-Sedimentation Coagulation. From: Hunt. Particulates in water.

of the collision function for collision of an arbitrary particle of 1 micron in diameter. For particles less than 1 μm , Brownian motion is the dominant collision mechanism. Particles from 1 to about 100 μm collide because of fluid shearing. For collisions of 1 μm particles with particles greater than 100 μm , differential settling is predominant.

Particle transport in aqueous systems is essentially a physical process, and is controlled by physical parameters such as temperature, velocity gradient, particle size, particle size distribution, particle density, and shape.

A floc particle consists of a small amount of solid, of density considerably greater than water, and a large amount of water. As a result of this the floc particle density is only slightly greater than the density of the water.

Lagvankar and Gemmell [4] and Tambo and Watanabe obtained the following relationship between bouyant density and floc size:

$$\rho_s - \rho_0 = kA^{-\alpha}$$

where $\rho_s - \rho_0$ is the floc bouyant density; A is the projected area of the floc; and α is an exponent which equals 0.338 by geometry consideration, and which equals 0.349 from measurements of floc < 1.5 mm. In both investigations it was found that k and α are a function of the hydrolyzing metal-primary particle concentration used in forming the floc suspension.

This equation shows that the density of a floc is inversely proportional to its size. As particles grow, their surface geometry

becomes complex resulting in a progressively poorer fit and progressively lower floc density. Larger flocs are weaker because of the poor fitting inherent with their formation.

Observation of floc particles made by Boadway [18] reveals that the small particles appear as dense spheroids while larger particles are a loose agglomeration of the denser small particles. The particles are irregular in shape, but have an average shape of a prolate spheroid with length twice its width. Although some of the particles appear to have discontinuities through which water could pass, the majority appear substantial enough that fluid would likely flow around with little or no leakage through the particle.

Because of their irregular shape, the size of floc particles can not be too closely defined. Usually it has been assumed spherical with a diameter equal to the diameter of the sphere. However, when irregular particles are considered, the concept of diameter requires modification, and a mean diameter is defined.

There are several possible ways [19-24] to define mean diameter of a particle or a particle collection. Martin's definition of mean diameter is the measurement of length in a particular direction. An easy way to measure the length is to define a reference direction and make the measurement through a point midway between the top and bottom-most point of the particle. This measurement is illustrated in Figure 2-6.

Feret's definition of particle diameter is the length of the distance between two tangents on opposite sides of the particle profile.

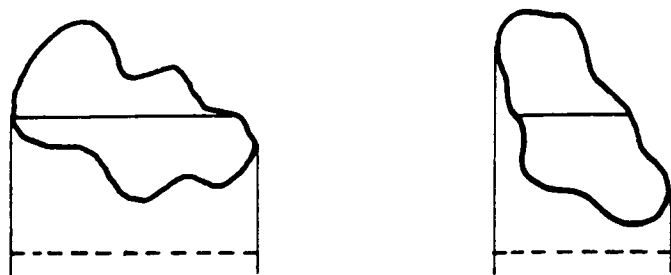


Figure 2-6. Martin's Diameter (solid lines bisecting particles) and Feret's Diameter (dashed lines).

The tangents must be parallel to an arbitrarily fixed direction.

This measurement is shown in Figure 2-6.

Another definition of mean diameter consists of measuring the length across the particle in several directions and taking the average of these. This measurement is illustrated in Figure 2-7. The intersection point should be as near to the centroid of the particle as possible.

Other definitions of diameter are based on the assumption that the length (l), breadth (b), and thickness (t) of the particle can be measured. Thus the diameter can be defined as the arithmetical average of the three dimensions:

$$d = (1/3) (l + b + t)$$

The dimensions also can be used to define the diameter as the length of the side of a cube having a volume approximately equal to that of the particle.

$$d = \sqrt[3]{l b t}$$

The measured diameters will be based on a large number of particles since there will be a considerable number of particles of varying shape and volumes having about the same mean diameter.

A suspension containing many particles of various sizes can be said to have a continuous size distribution. A cumulative particle size distribution is illustrated in Figure 2-8, where the accumulative number concentration (N) is plotted as a function of particle size (d). $N(d)$ denotes the total number of particles with diameter equal or less

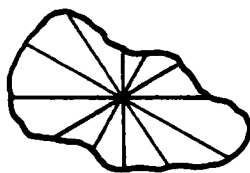


Figure 2-7. Measurement of Mean Diameter in Several Directions.

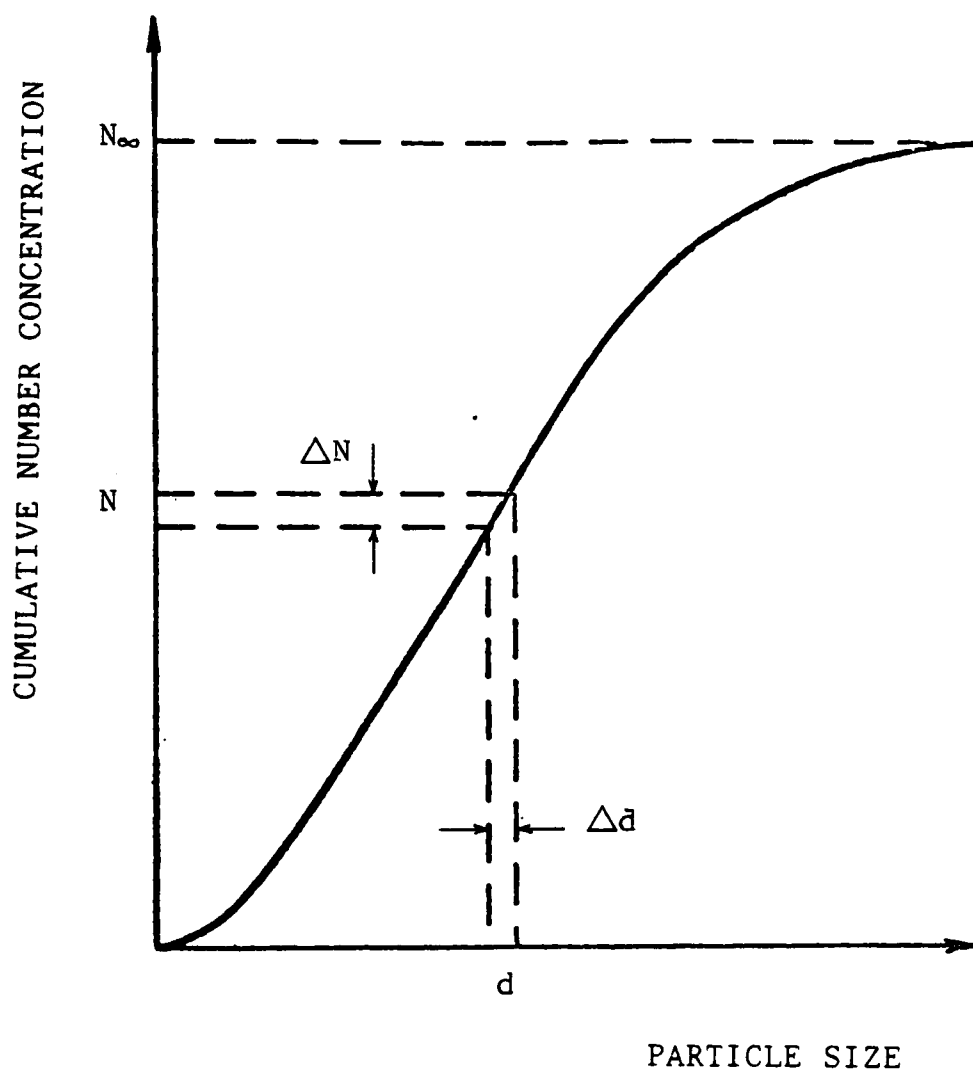


Figure 2-8. Cumulative Particle Size Distribution.

than the mean diameter ($\bar{d}$). The total concentration of all the particles is given by N . The slope of this curve, $\Delta N(d)/\Delta(d)$ or $d(N(d))/d(d)$, is called a particle size distribution function $n(d)$.

$$n(d) = d(N(d))/d(d)$$

The other measures of particle size are commonly used. The number mean diameter ($\bar{d}_{10}$), the surface mean diameter ($\bar{d}_{20}$), and the volumetric mean diameter ($\bar{d}_{30}$).

$$\bar{d}_{10} = \frac{\sum_{i=1}^n \Delta N_i d_i}{N}$$

$$\bar{d}_{20} = \sqrt{\frac{\sum_{i=1}^n \Delta N_i d_i^2}{N}}$$

$$\bar{d}_{30} = \sqrt[3]{\frac{\sum_{i=1}^n \Delta N_i d_i^3}{N}}$$

$\bar{d}_{20}$ is the square root of the second moment about the origin. It is a particularly useful mean when the surface behavior of the particle is being considered. $\bar{d}_{30}$ is the cube root of the third moment about the origin and is particularly useful when one is interested in the contribution of particles of various sizes to the total mass of the particles in a given sample. In general, these diameters are related to the arithmetic mean diameter by the inequality $\bar{d}_{10} < \bar{d}_{20} < \bar{d}_{30}$. The magnitude of the differences among these diameters is another indication of spread in particle size of the sample.

The mean diameter is most often used in describing the particle size distribution. Another diameter that is commonly used is the median diameter d_{me} defined as the diameter at which the cumulative distribution has a value of 0.5. That is:

$$d_{me} = N(d)/N = 0.5$$

The area under the curve for $n(d)$ is the same on both sides of a vertical line passing through the median diameter. The modal diameter d_{mo} is defined as the diameter at which the greatest number of particles is clustered. This diameter is located at the maximum point of the curve for $n(d)$:

$$d(n(d))/d(d) = 0$$

A hypothetical size distribution of a particle sample illustrating the different mean diameters is shown in Figure 2-9.

Other properties commonly used are the dispersion, skewness, and kurtosis. The measure of dispersion most used is the standard deviation or its square, the variance or second moment.

$$\sigma^2 = \frac{1}{N} \int_0^{\infty} (d - \bar{d})^2 n(d) d(d)$$

The variance is taken about the mean diameter $\bar{d}$, and is equal to the moment of inertia of the area under the curve $n(d)$ about the vertical line passing through the centroid.

Skewness is defined in terms of the third moment about the centroid, and is given by

$$m_3 = \frac{1}{N} \int_0^{\infty} (d - \bar{d})^3 n(d) d(d)$$

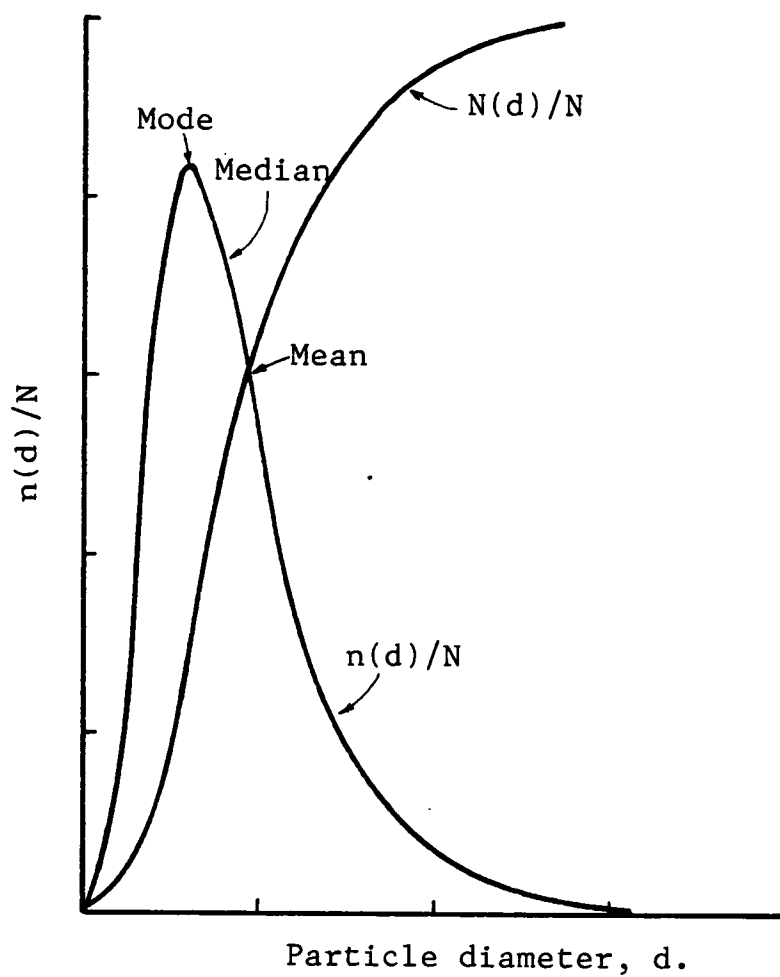


Figure 2-9. Hypothetical Size Distribution of a Particulate Sample.

The third moment is used to determine whether a distribution is symmetric or skewed about $\bar{d}$. Since all deviations in the equation for m_3 are cubed, negative and positive deviations cancel each other. Therefore, an m_3 equal to zero means the distribution is symmetric about $\bar{d}$. If m_3 is positive, the distribution is said to be right or positively skewed, and left or negatively skewed when m_3 is negative. A relative measure of skewness is used to eliminate any influence by the units in which the variables are measured.

$$\text{Skewness} = \frac{m_3}{(\sigma^2)^{2/3}}$$

It may be considered that the distribution is symmetric when $-0.5 < \text{Skewness} < 0.5$. The distribution is highly skewed when this value exceeds ± 1 .

The fourth moment m_4 is used to interpret the flatness or peakedness of a distribution curve:

$$m_4 = \frac{1}{N} \int_0^{\infty} (d - \bar{d})^4 n(d) d(d)$$

Another relative measure known as the Kurtosis of a distribution may be used to obtain this information.

$$\text{Kurtosis} = \frac{m_4}{(\sigma^2)^2}$$

The Kurtosis of a normal distribution is around three. For values less than three the curve flattens out and for values greater than three it becomes more peaked.

Lawler, O'Melia, and Tobiason [25] conclude that the particle concentration and size distribution have extensive, complex, yet predictable effect on the performance of individual treatment units and on overall plant performance. Solid-liquid separation processes and coagulation facilities should be designed to reflect important characteristics of the solids to be treated, including particle concentration and size distribution.

Most coagulation operations in the treatment of surface water are directed toward the removal of turbidity. The reason for this is that microorganisms capable of transmitting disease fall into the colloidal size range, and they must be removed. Another reason is one of aesthetics. People generally want clear water.

There are several methods commonly used in the design and control of the coagulation process for turbidity removal. One of the most widely used is the jar-test. Historically, the jar-test has served as an empirical means of estimating flocculation parameters. This test attempts to simulate the full-scale coagulation/flocculation process. The apparatus consists of six sample jars which are stirred by individual mechanically operated stirrers. Samples to be coagulated are placed into the jars. Coagulant agents are added during a short period of rapid mix, followed by a longer period of slow mix. After the samples are coagulated they are allowed to settle for a specific period of time. The samples are then analyzed for clarity. Supernatants may be analyzed for turbidity, pH, residual coagulant, or other parameters.

Jar-test techniques have been profusely studied by several investigators [46-49]. Camp [12] used a 2-liter beaker and a Phipps and Bird multiple stirrer mixing device. To reduce the continuing rotation of the water after the flocculating paddles are stopped, he used statots.

The University of Florida [6,7] developed a new type of equipment. They used rectangular plastic jars with a sample tap at a point 10 cm below the water surface, which may be used either with a top-entering stirred or with a magnetically-activated blade. This equipment has several advantages: (1) plastic jars are less fragile, (2) samples are easy to withdraw, (3) reduce the rotation of the water in the jars during the settling period. Observations of flow conditions indicate that the flow becomes laminar within 30 sec after stopping agitation. Apparently, this brief period required to slow the water down is analogous to the turbulence at the settling basin inlet, (4) the acrylic plastic walls are less heat-conductive than the glass walls of the other jars. No material change in temperature of sample occurs during testing.

The jar-test technique is usually used to study optimum turbidity removal. The information is obtained by plotting the turbidity of the supernatant for different dosages over time of settling.

Turbidity is usually measured with a turbidimeter. In water treatment, turbidimeters have been standardized only to the extent that the light scattered at an angle of 90° to an incandescent lamp source is measured.

Scattering by an individual particle depends [26] on its size, refractive index, and shape, and the wavelength of the incident light. For a given weight (or volume) of material, initially composed of monodisperse singlets of very small size so that Rayleigh's law is observed ($d < \lambda/10$) undergoing coagulation the suspension turbidity will increase as the third power of the ratio of the aggregate radius to the singlet radius, since the number of particles per unit volume in the system decrease inversely as the third power of the aggregate radius, while the scattering of each aggregate increases as the sixth power of this radius. The turbidity is the product of these quantities; that is,

$$T = \sum_{i=1}^n n_i \pi r_i^2 (K_{sca})_i$$

where K_{sca} equals $32 \alpha^4 (m-1)^2 / 27$.

When the initial singlets and their aggregates are comparable in size to the wavelength of the incident light ($d \sim \lambda$), the scattering per aggregate is proportional to the fourth power of its radius and the turbidity of a given weight of material will increase linearly with the ratio of the aggregate radius to the singlet radius. K_{sca} equals $2 \alpha^2 (m-1)^2$.

For large aggregates with small refractive indices, and arbitrary values of $\alpha(m-1)$, the scattering is approximately proportional to (1) the fourth power of the radius in the range $\alpha < 20$; (2) the third power of the radius for the range $20 < \alpha < 30$; and (3) the second power of the radius in the range $\alpha > 30$. Thus in one portion of the

anomalous diffraction regime, the turbidity of a coalescing system is insensitive to changes in the aggregate diameter ($20 < \alpha < 30$), and decreases for larger aggregate diameters ($\alpha > 30$), K_{sca} equals $2 - (4 \sin \rho) / \rho + 4 (1 - \cos \rho) / \rho^2$ and ρ equals $2\alpha(m-1)$.

For still larger aggregates ($1 \ll \alpha(m-1) \ll \alpha$), the scattering is proportional to the square of the aggregate radius so the turbidity of the system will always decrease with the increasing diameter of the aggregate. K_{sca} is 2.

Even when the turbidity measurement provides extremely useful information, it does not give complete information on the size, mass, or type of particle. Black and Hannah [5] show that for small particles, scatter is symmetric in forward and backward directions about 90° , with the scattered intensity at 0° and 180° , twice the scattered intensity at 90° . This is shown in Figure 2-10.

As particle size increases, scattered waves from different parts of the same particle begin to exhibit mutual interference, as shown in Figure 2-11. The net effect is a greater measured intensity of light scattered in the forward direction as shown in Figure 2-10. The larger particles scatter about 6 times as much light at 15° as it does at 90° . Very large particles typically found in treated water scatter more than 100 times as much light at 15° as at 90° . Therefore, a water containing asbestos fibers, viruses, or humic substances may have a large particle number concentration, but have low turbidity. Larger particles such as clay or plankton which have particle diameters approximating the wavelength of visible light scatter light more effectively and thus would yield higher turbidities.

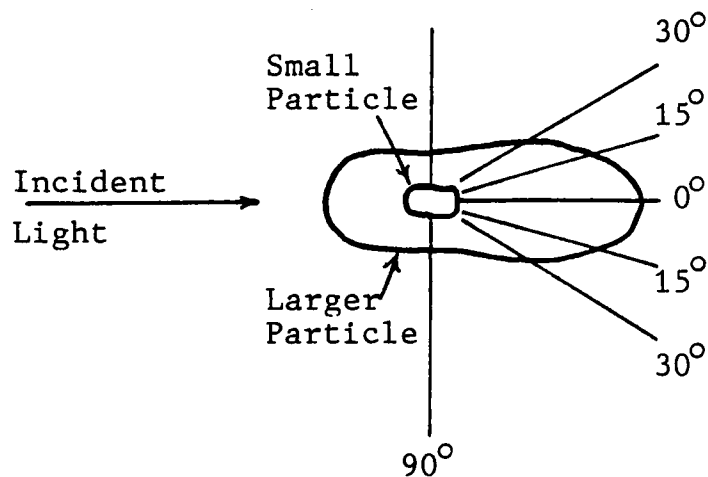


Figure 2-10. Scattering Intensities from Small and Large Particles as a Function of Angle.

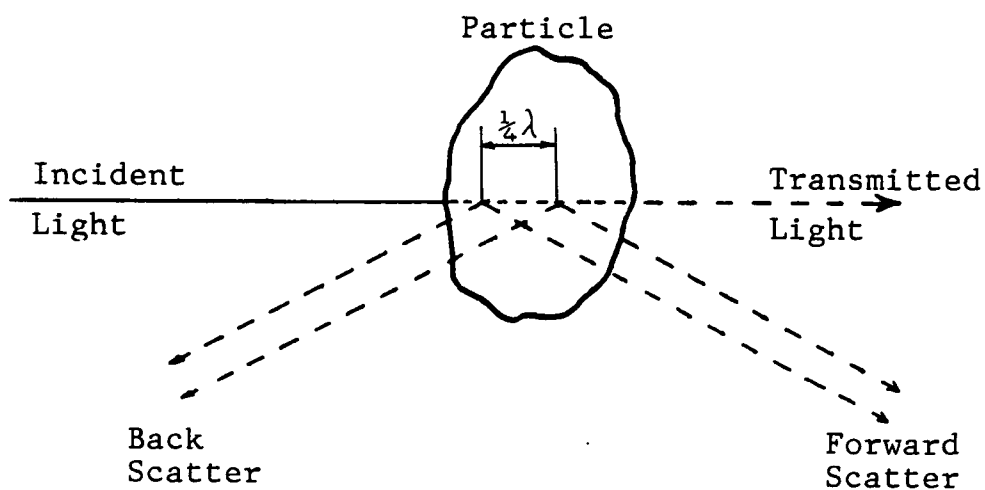


Figure 2-11. Interference of Light Scattered by a Large Particle.

Several methods to measure particle size have been used. Photographic and turbidimetric methods have been used to evaluate changes in floc size or number of particles. Fair and Gemmel [27] used a Couette mixer to flocculate suspensions under different velocity gradients and then compared floc size photographically. Boadway's observation [18] of particle size and floc size distribution was made using a 35 mm camera with macrolens. The measurement of floc particles were made projecting the negatives on a large screen using a magnification such that 1/10 in. on the screen equalled 50 microns of object size. Hudson [28,29] and Harris [30] evaluated particle content turbidimetrically using a paddle mixer. Hudson assumed that the small size represented turbidity particles, and the large size represented floc particles. Swift and Friedlander [31] flocculated latex suspensions in a Couette mixer and measured particle size with a Coulter Counter. Hannah, Cohen, and Robeck [32], and later Ham and Christman have used the Coulter Counter for counting and sizing alum and ferric iron floc particles. Lately several investigators have reported information on particle size and particle distribution by using a HIAC particle counter. Basically this instrument is able to count data in six particle size ranges. The sample is passed through a light beam, blocking the light. Particles interrupting this beam in the sensing zone cause a reduction in the amount of light reaching a photodetector. The resultant voltage pulse is directly proportional to the maximum projected area of each individual particle. The high fluid shear as the sample passes through the sensor has raised questions on the validity of these measurements for floc particles. The resulting

sizes may be more a reflection of relative floc strength rather than a true size measurement.

CHAPTER III

EXPERIMENTAL PROCEDURE

Experiments were conducted using a modified jar-test technique. Six 2-liter plastic rectangular jars with sampling taps 10 cm below the surface of the water were used. A Phipps and Bird multiple stirrer mixing device was used, as shown in Figure 3-1 and Figure 3-3. The equipment was calibrated according to a published procedure, and the calibration curve is shown in Figure 3-2.

The impeller speed of the paddle was set at 50 rpm. This corresponds to a velocity gradient (G) of approximately 42 sec^{-1} which lies in the traditional range of velocity gradients in water plant flocculation. The same speed was maintained during all of the experiments.

Raw-water from the Tennessee River was obtained from the Mark B. Whitaker Water Treatment Plant, every day. As the experiments were performed during May, unusually high turbidities were present in the water because of heavy rains during that month. The water was stored overnight in the laboratory to bring it to room temperature and to eliminate the settleable particles. The pH of the raw water was between 7.5-8.0.

Stock solutions of alum were prepared by diluting aluminum sulfate $\text{Al}_2(\text{SO}_4)_3 \cdot 18(\text{H}_2\text{O})$ in distilled water. To avoid problems of alum aging, the solutions were discarded after reaching a maximum age of one week.

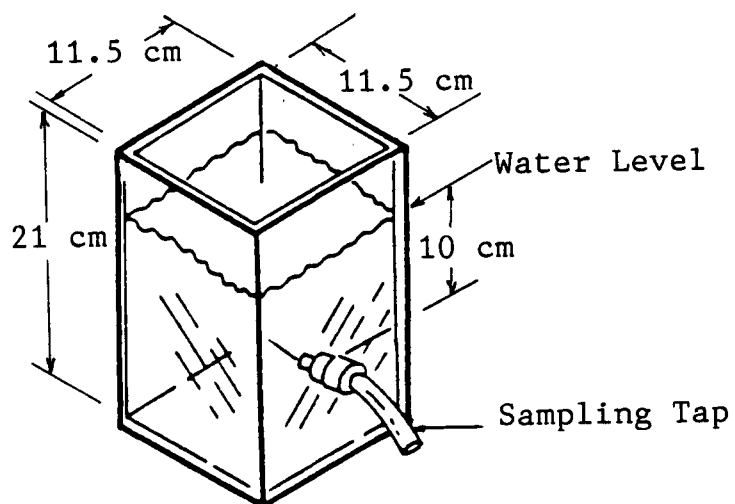


Figure 3-1. Two-Liter Plastic Jar for Modified Jar-Test.

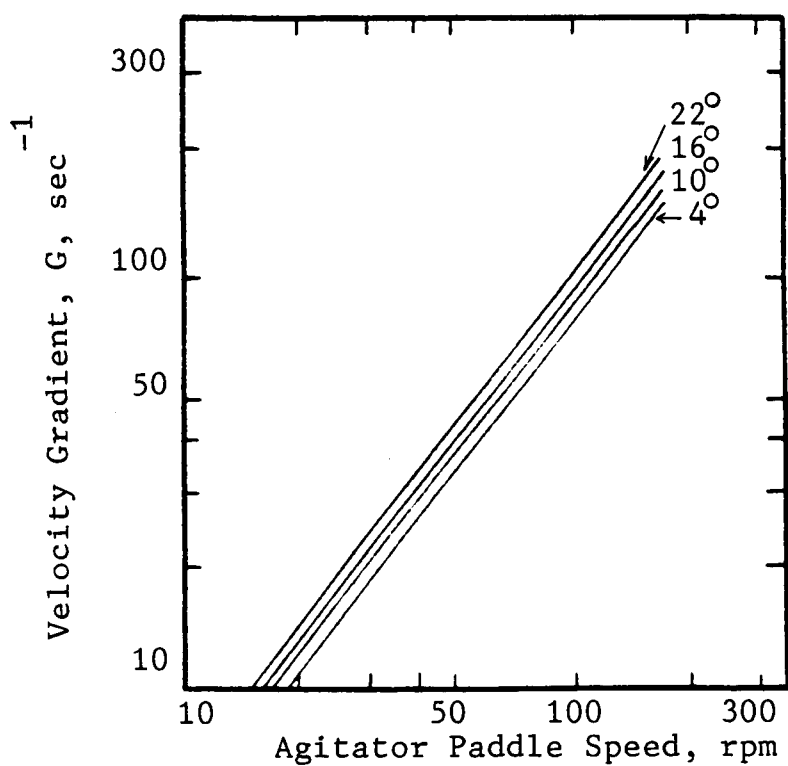


Figure 3-2. Velocity Gradient vs rpm for Two-Liter Square Jar, Using Phipps and Bird Stirrer.

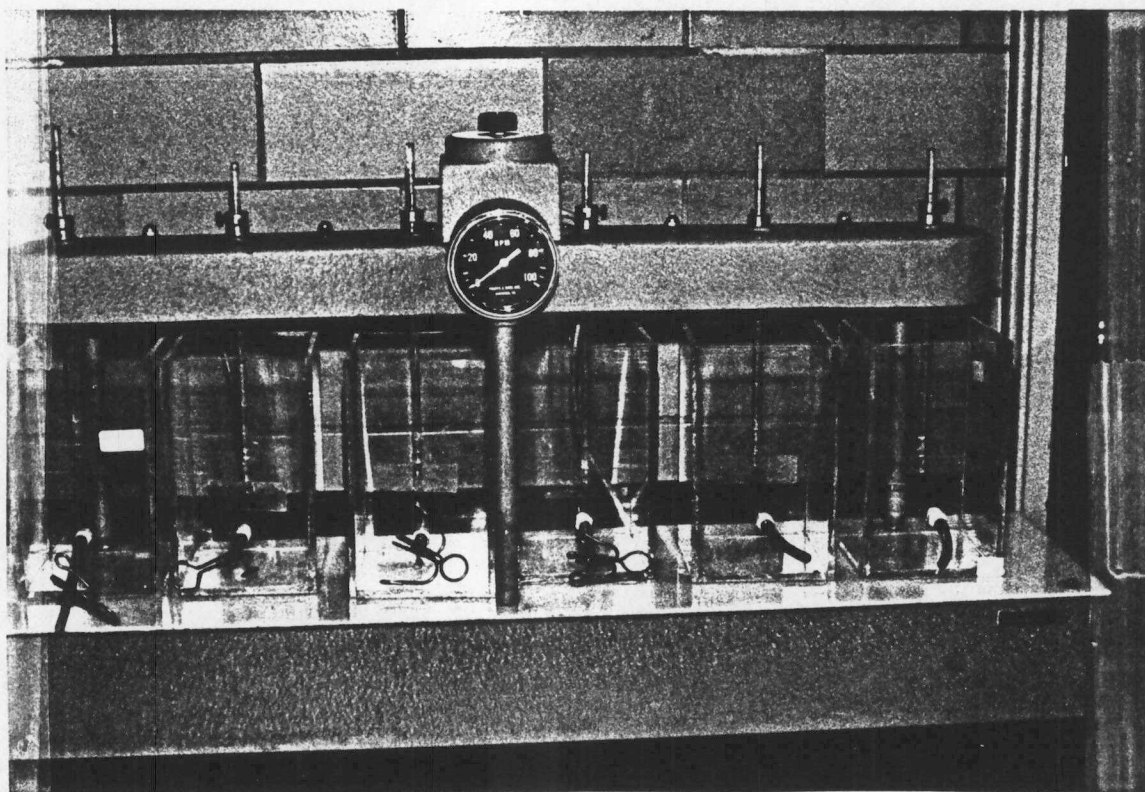


Figure 3-3. Phipps and Bird Multiple Stirrer with Two-Liter Square Jars.

Prior to the jar-test, the water was analyzed for particle size distribution using a HIAC/ROYCO Model 4100, with a high concentration sensor HCS Model 600, as shown in Figure 3-4. The particle size threshold for each of the six channels was selected by correlating it with the calibrating curve of the sensor. Particle sizes were counted in ranges from 10 to 600 microns.

Volumes of 10 ml were analyzed using a HIAC Automatic Bottle Sampler, as shown in Figure 3-4, in combination with the particle counter set in the volume mode. This mode allows the counter to analyze a preselected volume of sample. A diagram of the operating cycle is shown in Figure 3-5. Because of the high concentration of particles, the raw-water was diluted in distilled water in a proportion 1:20, to avoid coincidence error (the probability of counting two or more small floc particles as one apparent larger particle).

Raw-water was also analyzed for turbidity using a HACH turbidimeter Model 2100-A, always gently swirling it to avoid the settling of particles before the measurement.

Jar-tests were run adding alum doses of 10, 15, 20, 25, 30, and 35 mg/L through a pipette to the hub of the impeller, during 2 min of flash mixing (100 rpm). The pipettes were flushed with a small quantity of water immediately after the addition of the coagulant. This was followed by 20 min of slow mixing (50 rpm).

Samples were withdrawn through the sampling tube just before the mixing was shut off and then at intervals of 1, 2, 5, 10, 15 and 20 min following termination of the period of flocculation. Each time a small amount of water was discarded before withdrawal of the

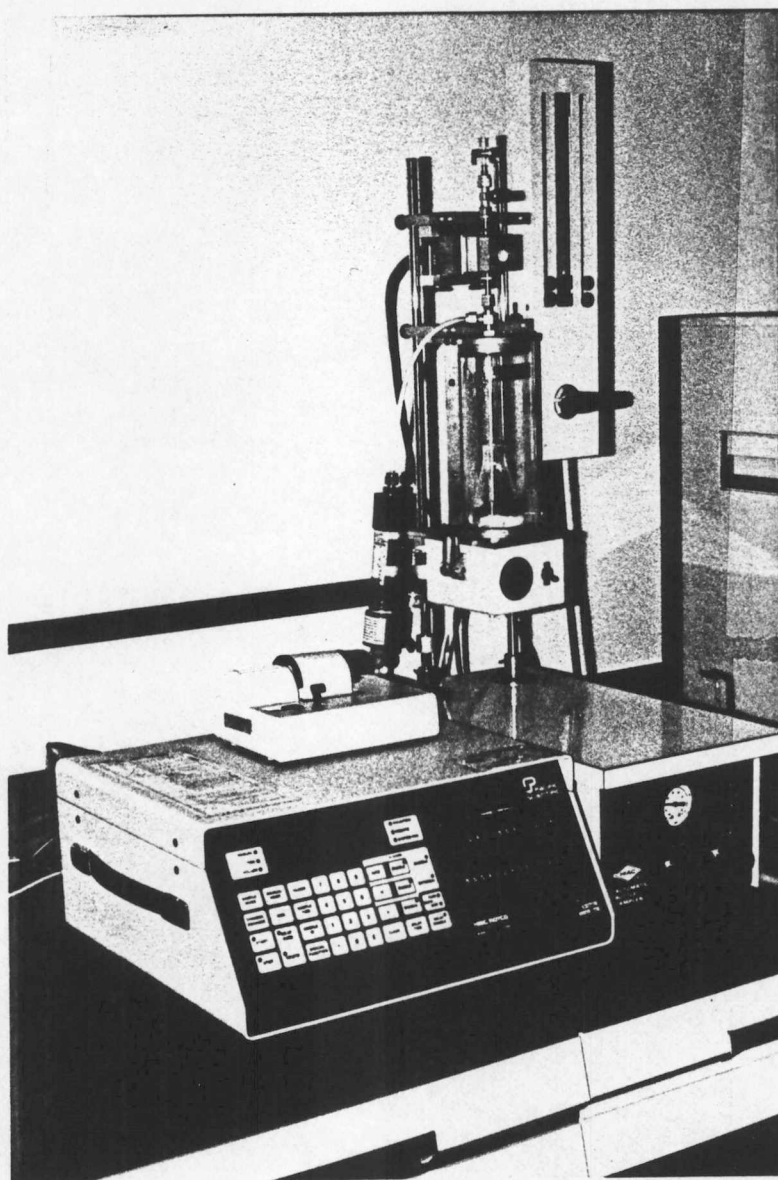


Figure 3-4. HIAC/ROYCO Model 4100 with Automatic Bottle Sample.

AUTOMATIC BOTTLE SAMPLE

HIAC MODEL 4100

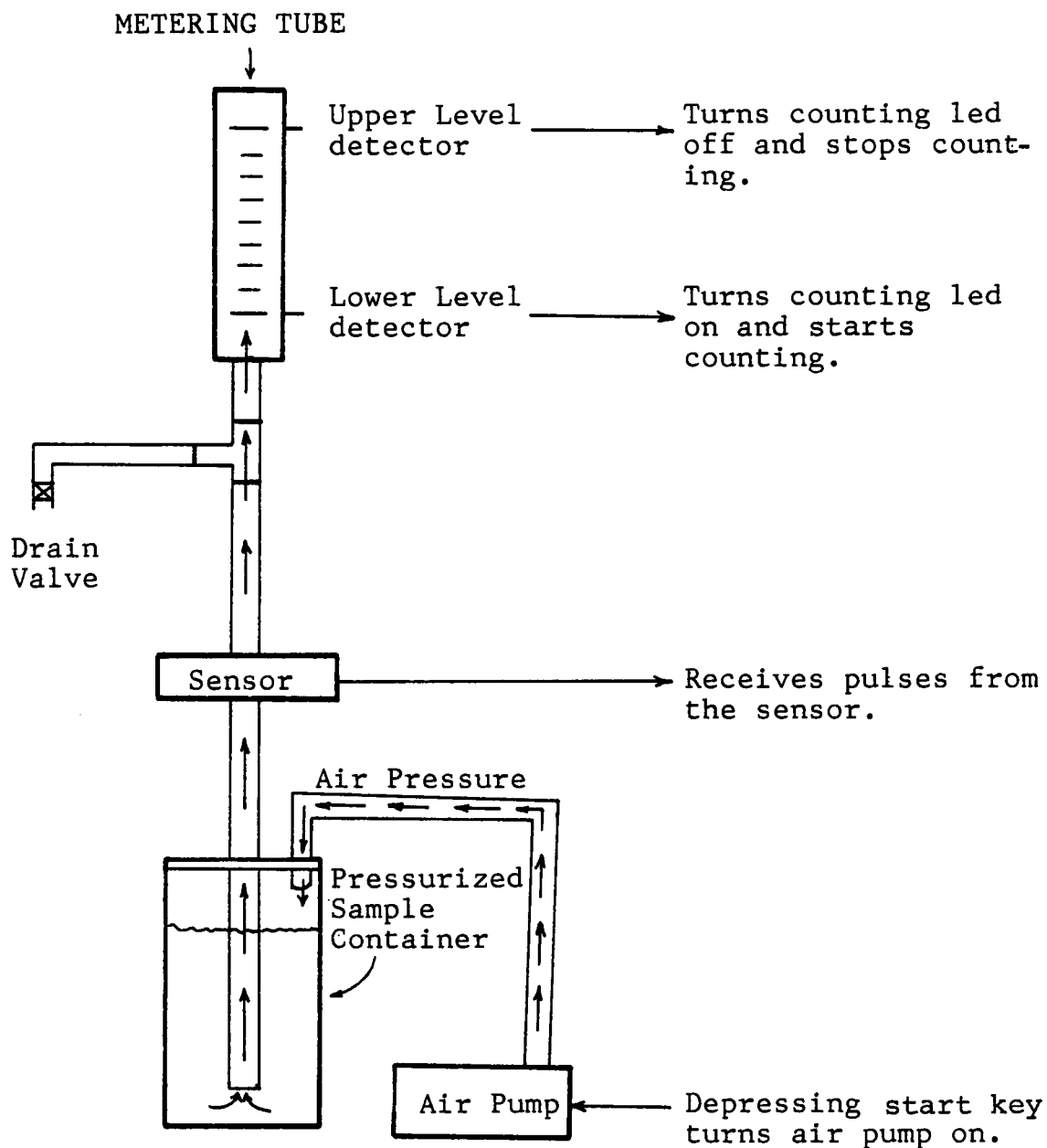


Figure 3-5. Diagram of the Operating Cycle of HIAC Model 4100 Operating with Automatic Bottle Sample.

sample in order to flush the sample tube. The samples were immediately analyzed for turbidity, always swirling them to resuspend the particles before a measurement was made.

Several techniques were used to try to measure the floc particle sizes. A HIAC particle counter was used to determine the particle size. As the particles passed through the instrument to be counted, they were subjected to high velocity gradients created by drawing the suspension through the Automatic Bottle Sample. This produced a break-up of the floc particles that resulted in a larger count of small particles. When samples were analyzed, none of the large particles that could visually be cataloged in a range of 0.5-1.0 mm appeared in the particle counter test. Evidence of this is shown in Table 3-1.

An attempt to measure the particle size was made by using a Polaroid camera mounted over a Balplan microscope. The sample was placed on a 2-mm grid divided into units of 0.01 mm, and pictures of the flocs were taken. The major problem was that the volume of the sample was not representative of the volume in the 2-liter beaker and a large sampling error was introduced. Finally observations of the flocs just above the sampling level were made using a 35 mm camera with macro lens which was mounted on a tripod. A black calibrated metal sheet was placed inside the jar 10 mm from the inner wall. The jars were illuminated from underneath, and from the side, accenting the floc particles in contrast to the black background. The equipment and light arrangement are shown in Figure 3-6. Photographs, such as that shown in Figure 3-7, were taken using a setting of F2.5 to give a depth of field only slightly less than the distance between the

Table 3-1. Particle Count by Using Two Different Techniques.

Range (μm)	HIAC Particle Counter (Number part/mL)	Photographical Method (Number part/mL)
SAMPLE 1		
10- 75	152	-
75-125	40	3
125-200	9	6
200-400	1	28
400-600	0	40
600-900	0	15
SAMPLE 2		
10- 75	776	-
75-125	142	32
125-200	5	93
200-400	0	58
400-600	0	38
600-900	0	5

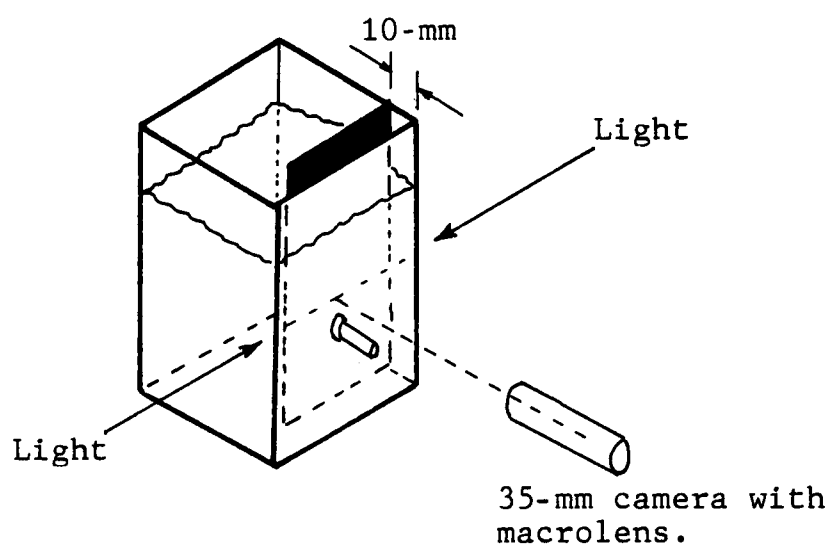


Figure 3-6. Diagram of Equipment Used to Photograph the Floc Particles.

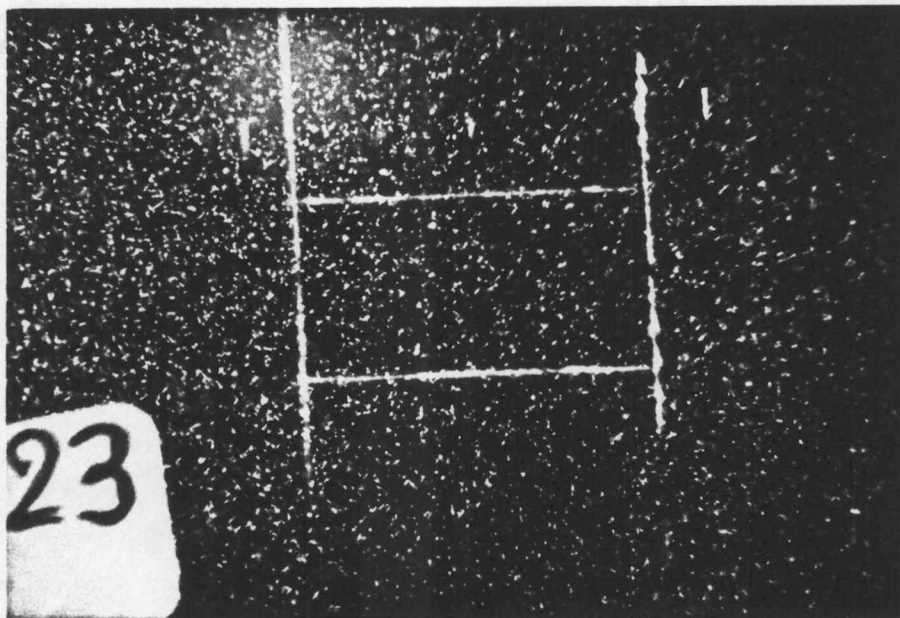


Figure 3-7. Macrophoto of Floc Particles Taken at the Moment the Mixing was Shut Off.

a depth of field only slightly less than the distance between the metal sheet and the jar.

Three photographs were taken at the moment the mixing was shut off. Usually the first and third one were discarded. The first one because the floc particles were still in movement when the picture was taken, and the third one because the large particles had started settling. Before the pictures were taken, it was necessary to remove the bubbles from the wall of the jar, to avoid interferences in the photographs.

At the end of the settling periods, 100 mL samples were withdrawn through the sampling tap. The samples were analyzed to measure particle size using the particle counter with the same sensor and volumes of 10 mL.

CHAPTER IV

COMPUTER PROGRAM DEVELOPMENT

Several investigators [39,40] have presented mathematical models for the relationship between concentration and settling velocities.

It is common practice to assume that the particles in the suspension are discrete and nonflocculating, and then calculate terminal velocities from Stokes' law.

Based on the theory of quiescent sedimentation of discrete particles, the computer model, COVT, was developed to calculate the dimensionless concentration $C(t)/C(0)$ at time t . Figure 4-1 contains the flow diagram of computer program COVT. The computer program was written in Basic language for the Apple IIe. A listing of this program may be found in Appendix B.

The program, COVT, requires as inputs the number of floc particle ranges in the analysis, N , (a maximum of ten ranges). It also requires the upper size of each range given in microns, $D(I)$, and the number of floc particles in each range, $NP(I)$. Other program inputs are the floc density, $PDENS$, the water density, $WDENS$, and the viscosity of the water, $VICS$.

Size and density are two of the most important parameters in the settling characteristics of the floc. Attempts have been made to calculate these parameters. One of the major difficulties has been in defining an enclosed volume for the floc. For simplicity it has been assumed spherical.

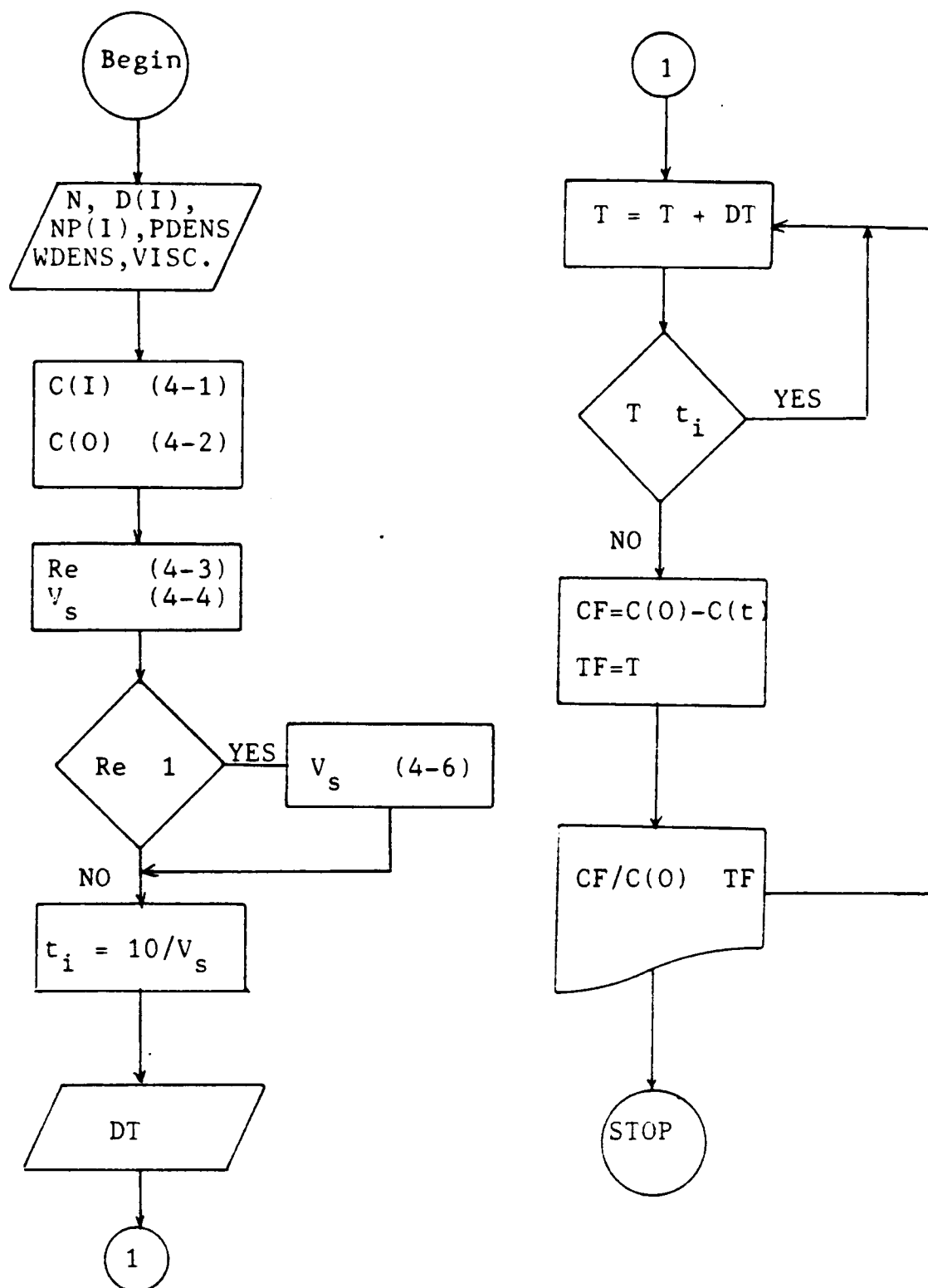


Figure 4-1. Flow Diagram of Computer Program COVT.

In this research the floc particles were assumed to have a diameter equal to the average between the upper and lower limits of each range.

For simplicity it was assumed that all the flocs had the same density. An average floc density [13] of 1.002 was used, mainly because the variation is so small that it does not induce a large error.

The computer program COVT first calculates the initial concentration $C(0)$ as the addition of all the floc concentrations in each one of the different size ranges.

$$C(I) = (3.14159/6) DM(I)^3 NP(I) PDENS \quad (4-1)$$

$$C(0) = \sum C(I) \quad (4-2)$$

where $C(I)$ is the floc particle concentration of each range of particles expressed as a mass per unit of volume.

Next, the program COVT, assuming laminar flow, calculates the Reynolds number, Re for each range as:

$$Re = dp \rho_1 V_s / \mu \quad (4-3)$$

and the settling velocity

$$V = g (\rho_s - \rho_1) dp^2 / 18 \mu \quad (4-4)$$

where V_s is the particle settling velocity; g the acceleration of gravity; ρ_s the mass density of the floc particle; ρ_1 the mass density of the fluid; dp the floc particle diameter; and μ the absolute viscosity.

For Reynolds number larger than one, the program, COVT, assumes flow in the transition zone. In this zone the Newton's drag coefficient, C , can be approximated by:

$$C = 18.5 / (Re)^{0.6} \quad (4-5)$$

and the terminal velocity is given by:

$$V_s = [0.7063 (\rho_s - \rho_l) d_p^{1.6} \rho_l \mu^{-0.6}]^{0.714} \quad (4-6)$$

Then the program, COVT, calculates the settling time for each set of particles ($t = L/V$) where L is the depth between the surface of the water and the sampling tube. This depth was considered fixed and equal to 10 cm. This settling depth was considered too small to permit much contact between particles, so no differential sedimentation was considered in this study.

Entering an increment of time DT , the program calculates the ratio of concentration $C(t)/C(0)$, during the first 30 minutes of settling at intervals DT . Based on the uniform initial concentration assumption, it was assumed that in every horizontal plane, flocs of all sizes were present. Assuming that the large flocs settle first, and already knowing the settling times between the surface of the water and the sampling tap, it was possible to calculate the concentration of flocs at each interval of time by subtracting from the initial concentration $C(0)$ all those concentrations having settling times less than the time t .

The program finally tabulates the results of values for $C(t)/C(0)$ versus t .

CHAPTER V

DATA ANALYSIS

Prior to coagulation, a counting and sizing of particles in the raw water was performed, using a HIAC particle counter. Turbidity, pH, and temperature also were measured. These data are summarized in Table 5-1.

Table 5-1. Summary of Raw Water Analysis Data.

Diameter Interval d(lower) to d(upper) μm	Number of Particles in Raw Water Samples					
	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6
10 to 20	21497	24127	14650	17276	18997	11931
20 to 30	1119	770	638	803	813	652
30 to 70	88	20	24	65	30	51
Turbidity (NTU)	20.0	23.0	26.0	22.0	19.0	23.0
Temperature $^{\circ}\text{C}$	26.0	24.2	25.1	23.7	25.5	26.4
pH	7.9	7.9	7.8	7.8	7.8	7.7

A series of jar-tests were run, with alum doses varying from 10 to 35 mg/L. After 20 minutes the slow mixing was shut off, and floc particles were measured photographically. The floc particles

were measured to the closest 7.5 μm by projecting the 35 mm negatives on a large screen. Measures of the length, l , and breadth, b , across two perpendicular planes of reference (horizontal and vertical) were made for each particle. The error in measurement of the floc particles was estimated to be around $\pm 15 \mu\text{m}$. The mean diameter was defined as:

$$d = \sqrt[3]{l b (l + b)/2}$$

The results of measurements were analyzed to give the mean sizes by number, by surface, and by volume.

$$\bar{d}_{10} = \frac{\sum_{i=1}^k n_i d_i}{\sum_{i=1}^k n_i}$$

$$\bar{d}_{20} = \sqrt{\frac{\sum_{i=1}^k n_i d_i^2}{\sum_{i=1}^k n_i}}$$

$$\bar{d}_{30} = \sqrt[3]{\frac{\sum_{i=1}^k n_i d_i^3}{\sum_{i=1}^k n_i}}$$

in which d_i is the middle of class range i ; n_i is the number of particles measured in range i ; k is the number of particle size range;

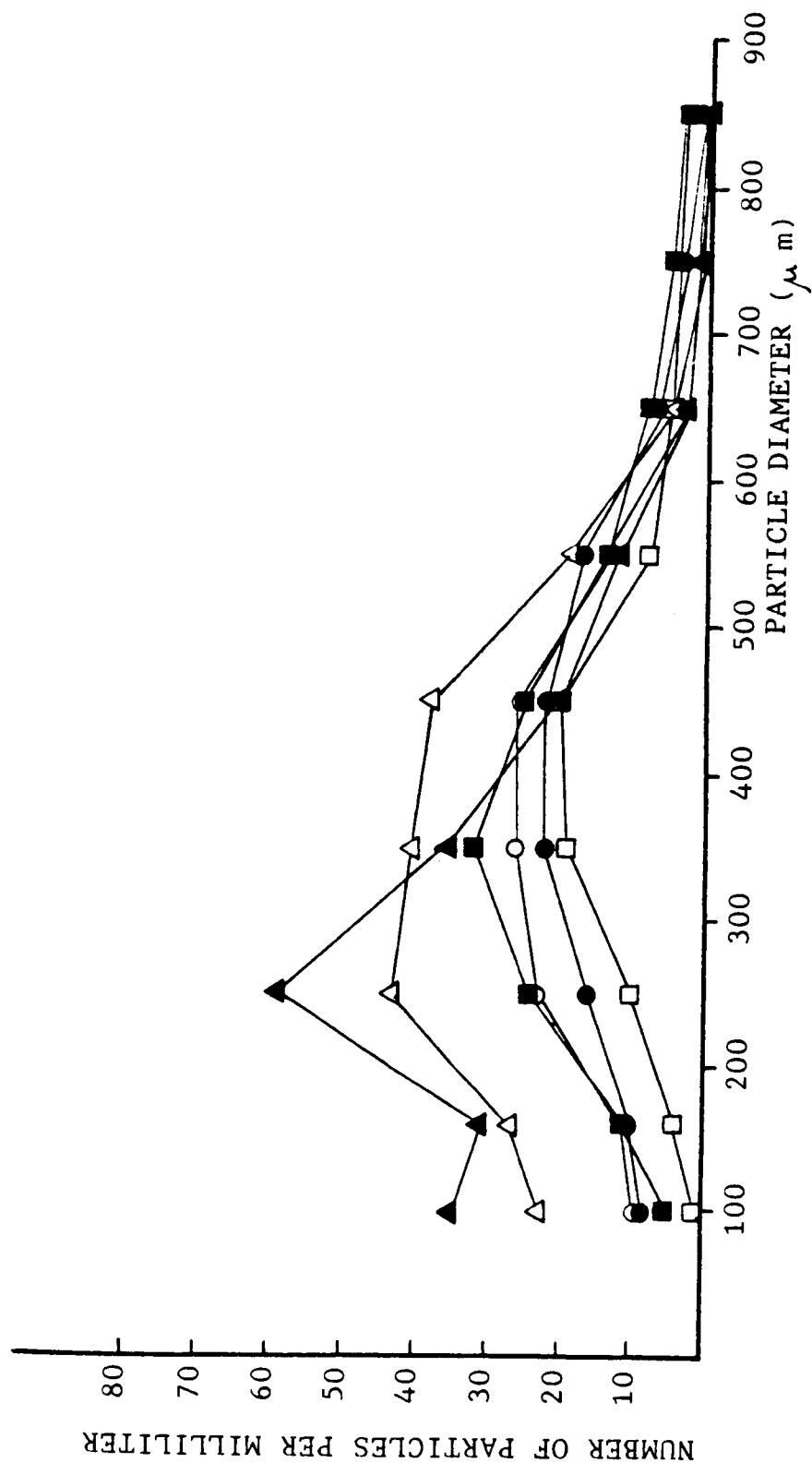
$\bar{d}_{10}$ is the number mean diameter; $\bar{d}_{20}$ is the surface mean diameter; and $\bar{d}_{30}$ is the volume mean diameter.

The distribution expressed in particles per millimeter and the total number of particles per millimeter N were also available from counts. A statistical analysis from the particle size distribution was made. A particle size distribution plotted as number of particles per milliliter versus diameter for two different tests are shown in Figures 5-1 and 5-2. The data for these two tests are summarized in Tables 5-2 and 5-3. A summary of the statistics of all the data is shown in Table 5-4.

A perfect normal distribution should have a kurtosis equals 3 and skewness equals zero. The statistical analysis showed that the particle distribution is normal for the optimum dosage and for those dosages near the optimum. For lower dosages the particle distribution is symmetric but the curve flattens out. For dosages larger than the optimum the distribution is highly right skewed and becomes more peaked.

The particles observed were generally not spherical. For the optimum dosage and dosages near the optimum the larger particles had an irregular shape and appear to have discontinuities. For dosages under or above the optimum the particles in general were smaller and appeared as spheroids. Figure 5-3 shows a micrograph of floc particles.

Samples were taken just before the mixing was shut off and then at 1, 2, 5, 10, 15, and 20 minutes of settling. The samples were analyzed and turbidity readings were recorded. Tables 5-5 and 5-6 summarized the jar-test results for two representative tests.



Data from jar test #2. Dosage (mg/L): 10 (○—○); 15 (●—●); 20 (□—□); 25 (■—■); 30 (△—△); 35 (▲—▲). Serie number: 19 to 24.

Figure 5-1. Particle Size Distribution from Jar-Test No. 2, Using Photographical Method.

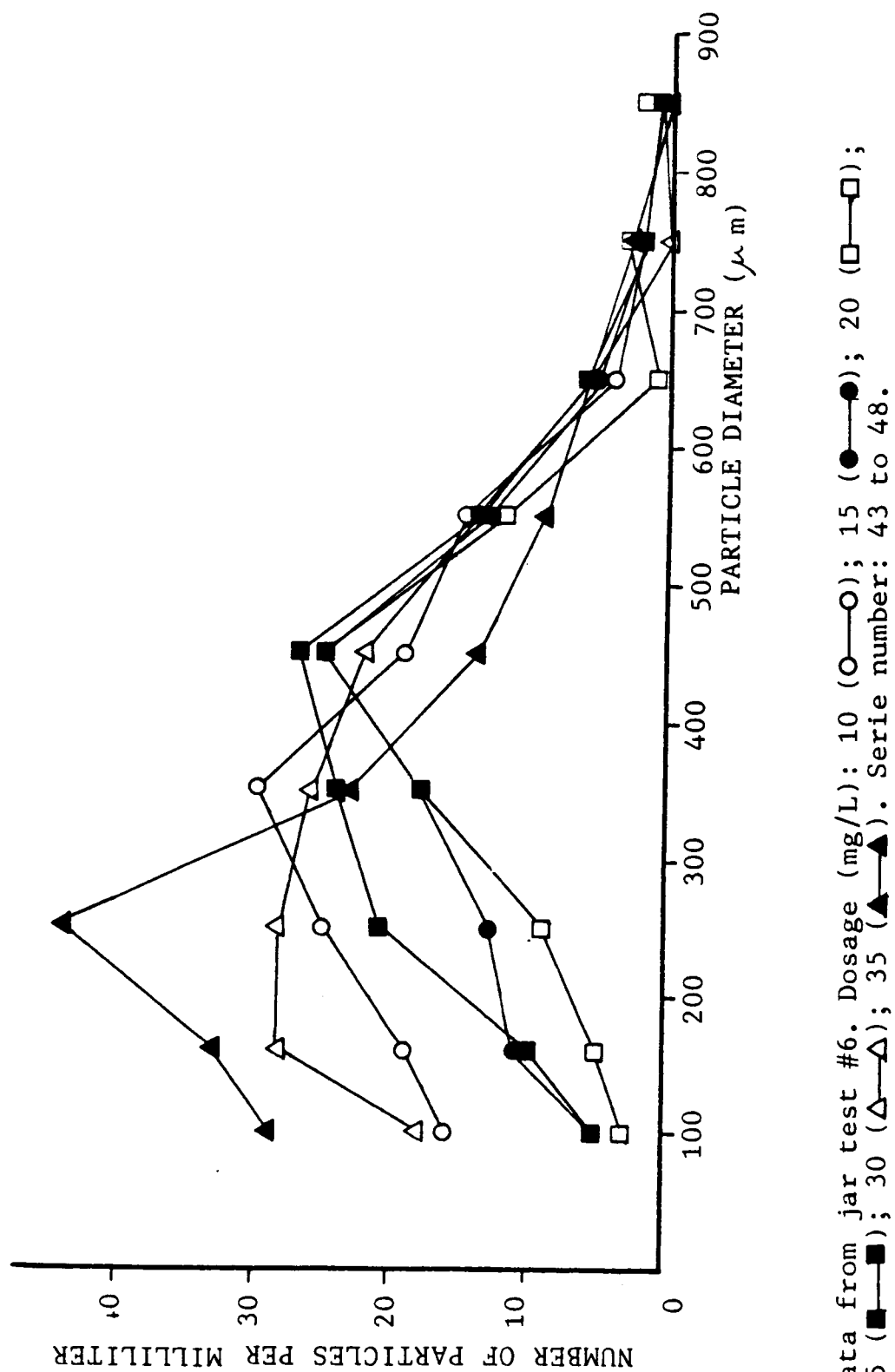


Figure 5-2. Particle Size Distribution from Jar-Test No. 6, Using Photographical Method.

Table 5-2. Particle Size Distribution for Jar Test No. 2.

Alum Dosage (mg/L)		10	15	20	25	30	35
Range	d	Test Number					
(μm)	(μm)	19	20	21	22	23	24
75-125	100	9	8	1	5	23	35
125-200	162.5	12	10	4	11	27	31
200-300	250	23	16	10	24	43	59
300-400	350	26	22	19	32	41	35
400-500	450	26	22	20	25	38	20
500-600	550	14	17	8	14	19	12
600-700	650	3	7	5	8	5	3
700-800	750	1	3	4	5	1	2
800-900	850	0	1	3	3	0	1
N		114	106	74	127	197	198
$\bar{d}_{10}$		349	387	434	393	322	280
$\bar{d}_{20}$		379	423	466	429	355	317
$\bar{d}_{30}$		403	453	496	462	382	353
$\sigma^2 \cdot 10^{-4}$		2.16	2.95	2.90	2.98	2.24	2.23
$m_3 \cdot 10^{-6}$		0.41	0.98	2.91	2.94	0.96	3.21
$m_4 \cdot 10^{-9}$		1.12	2.16	2.55	2.63	1.16	1.94
K		2.39	2.49	3.04	2.96	2.31	3.89
S		0.13	0.19	0.59	0.57	0.29	0.96

Table 5-3. Particle Size Distribution for Jar Test No. 6.

Alum Dosage (mg/L)		10	15	20	25	30	35
Range	d	- - - - - Test Number - - - - -					
(μm)	(μm)	43	44	45	46	47	48
75-125	100	16	5	3	5	23	29
125-200	162.5	19	11	5	10	28	33
200-300	250	25	13	9	21	28	44
300-400	350	30	18	18	24	26	23
400-500	450	19	25	25	27	22	14
500-600	550	15	13	12	14	14	9
600-700	650	4	5	1	6	5	6
700-800	750	2	2	3	2	0	3
800-900	850	1	1	2	1	1	0
N		131	93	78	110	147	161
$\bar{d}_{10}$		330	385	429	381	304	278
$\bar{d}_{20}$		369	419	477	412	344	320
$\bar{d}_{30}$		403	447	498	439	379	360
$\sigma^2 \cdot 10^{-4}$		2.74	2.69	2.71	2.46	2.63	2.54
$m_3 \cdot 10^{-6}$		2.44	0.90	1.02	1.24	2.54	4.18
$m_4 \cdot 10^{-9}$		2.12	1.95	2.19	1.72	1.86	2.25
K		2.83	2.69	3.00	2.83	2.69	3.49
S		0.54	0.20	0.23	0.32	0.60	1.03

Table 5-4. Summary of the Statistical Analysis.

Dosage (mg/L)	10	15	20	25	30	35
Jar Test	- - - - Volumetric Mean Diameter (μm) - - - -					
1	397	447	495	453	363	370
2	403	453	496	462	382	353
3	317	456	469	446	381	371
4	410	470	498	472	403	342
5	394	473	502	481	402	367
6	403	447	498	439	379	360
Jar Test	- - - - - Kurtosis - - - - -					
1	2.36	2.62	2.93	2.57	2.52	2.62
2	2.39	2.49	3.04	2.96	2.31	3.89
3	3.02	2.69	3.14	2.95	2.77	3.38
4	2.68	2.40	2.55	2.72	2.16	2.36
5	2.44	2.63	2.84	2.68	2.38	4.07
6	2.83	2.69	3.00	2.83	2.69	3.49
Jar Test	- - - - - Skewness - - - - -					
1	0.32	0.40	0.27	0.27	0.45	0.66
2	0.13	0.19	0.59	0.57	0.29	0.96
3	0.58	0.31	0.67	0.26	0.53	0.88
4	0.31	0.11	0.33	0.44	0.32	0.44
5	0.35	0.20	0.10	0.31	0.45	1.10
6	0.54	0.20	0.23	0.32	0.60	1.03

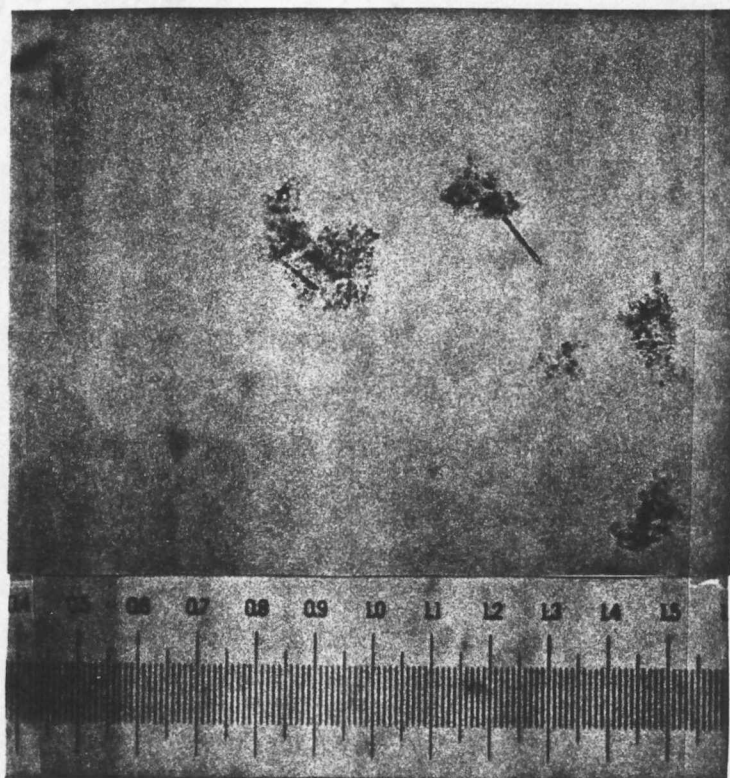


Figure 5-3. Macrophoto of Alum Floc.
(Scale shows units of 0.01 mm)

Table 5-5. Jar Test No. 2 Results

Parameter	19	20	Test number		23	24	
			21	22			
Rapid Mix							
rpm	100	100	100	100	100	100	
min	2	2	2	2	2	2	
Alum Dosage (mg/L)	10	15	20	25	30	35	
Flocculation							
rpm	50	50	50	50	50	50	
min	20	20	20	20	20	20	
Turbidity (NTU)							
after:	0 min	21.0	23.0	20.0	23.0	24.0	25.0
	1 min	20.5	22.5	20.0	22.5	24.0	25.0
	2 min	20.0	22.5	18.5	22.0	24.0	24.5
	5 min	16.0	14.0	9.0	10.5	19.5	20.0
	10 min	8.5	6.3	6.0	7.4	14.5	12.0
	15 min	5.5	3.1	2.7	3.5	7.3	7.5
	20 min	4.5	1.7	1.2	2.0	4.8	6.3
pH		7.8	7.6	7.4	7.4	7.2	7.0

Table 5-6. Jar Test No. 6 Results.

Parameter		43	44	Test Number		47	48
				45	46		
Rapid Mix							
rpm		100	100	100	100	100	100
min		2	2	2	2	2	2
Alum Dosage (mg/L)		10	15	20	25	30	35
Flocculation							
rpm		50	50	50	50	50	50
min		20	20	20	20	20	20
Turbidity (NTU)							
after:	0 min	24.0	24.5	22.0	24.0	24.5	25.0
	1 min	22.0	24.0	21.0	24.0	24.5	25.0
	2 min	20.5	22.5	20.0	23.0	24.0	24.5
	5 min	12.0	9.9	10.5	11.5	15.0	18.0
	10 min	5.5	5.9	4.4	5.7	10.5	14.5
	15 min	3.75	2.5	2.0	3.5	5.8	9.4
	20 min	3.4	2.0	1.0	2.9	5.2	6.8
pH		7.7	7.4	7.3	7.1	7.0	6.9

A three-dimensional plot of turbidity for two representative jar-tests are shown in Figures 5-4 and 5-5. These figures show the effect that different dosages of alum have on the same water sample. The optimum alum dosage can be determined from the shape of the line on the far right end.

At the end of the settling period the samples were analyzed for pH and particle counts and sizing. pH is recorded in Tables 5-5 and 5-6. Particles were measured and counted using the HIAC particle counter. Tables 5-7 and 5-8 record the data obtained for two different days.

Figures 5-6 and 5-7 show the particle size distribution for these two sets of data. It can also be seen that the mean diameter for these distributions is 15 μm . It was assumed that the particles present in the supernatants at the end of the settling periods corresponded to the small particles present in the water at the moment the photographs were taken. These particles are so small that they could not be seen in the picture. Their settling times are larger than the settling period of 20 minutes, so they were still in suspension at the time the supernatants were analyzed.

Figures 5-6 and 5-7 show that the number of particles in the raw water is drastically reduced as the particles agglomerate in the process of coagulation/flocculation. Comparing Figure 5-6 with Figure 5-1 (page 47) it can be seen that those alum dosages that produce a larger reduction in the number of particles in the range 10 to 20 μm , correspond to those alum dosages that produce a particle size distribution with a larger mean diameter. This effect can clearly be seen

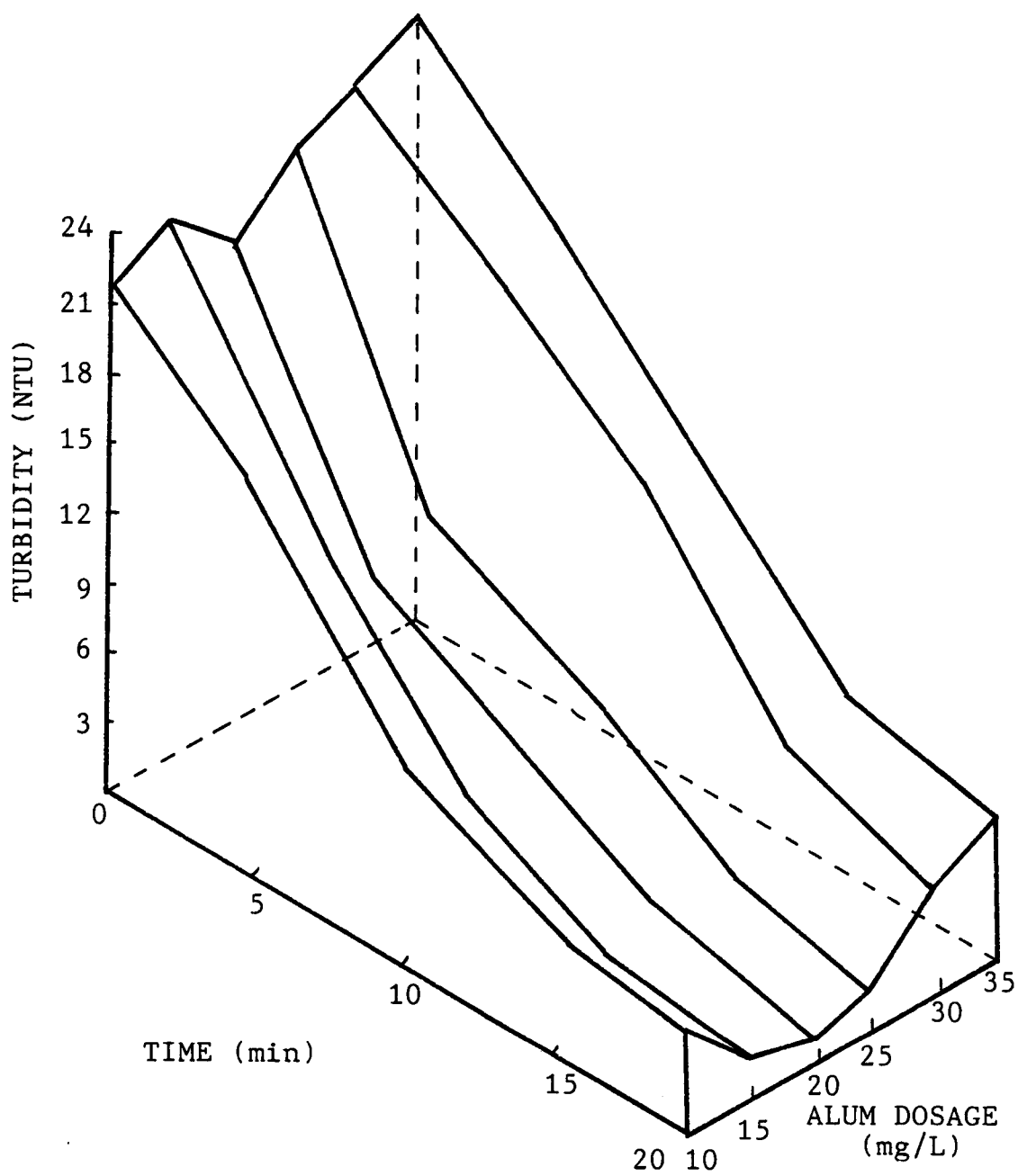


Figure 5-4. Settling Curves from Jar-Test No. 2 Data.

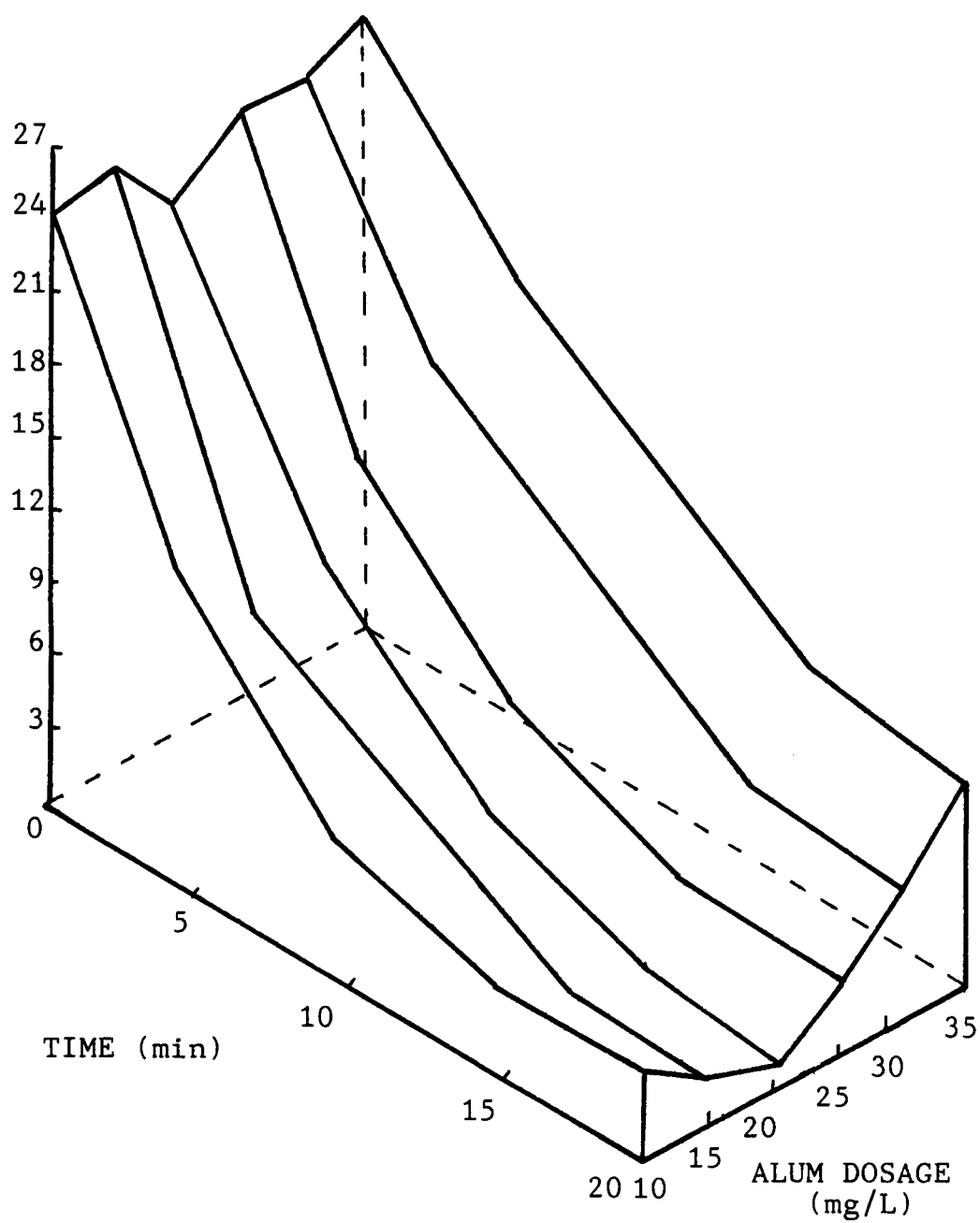


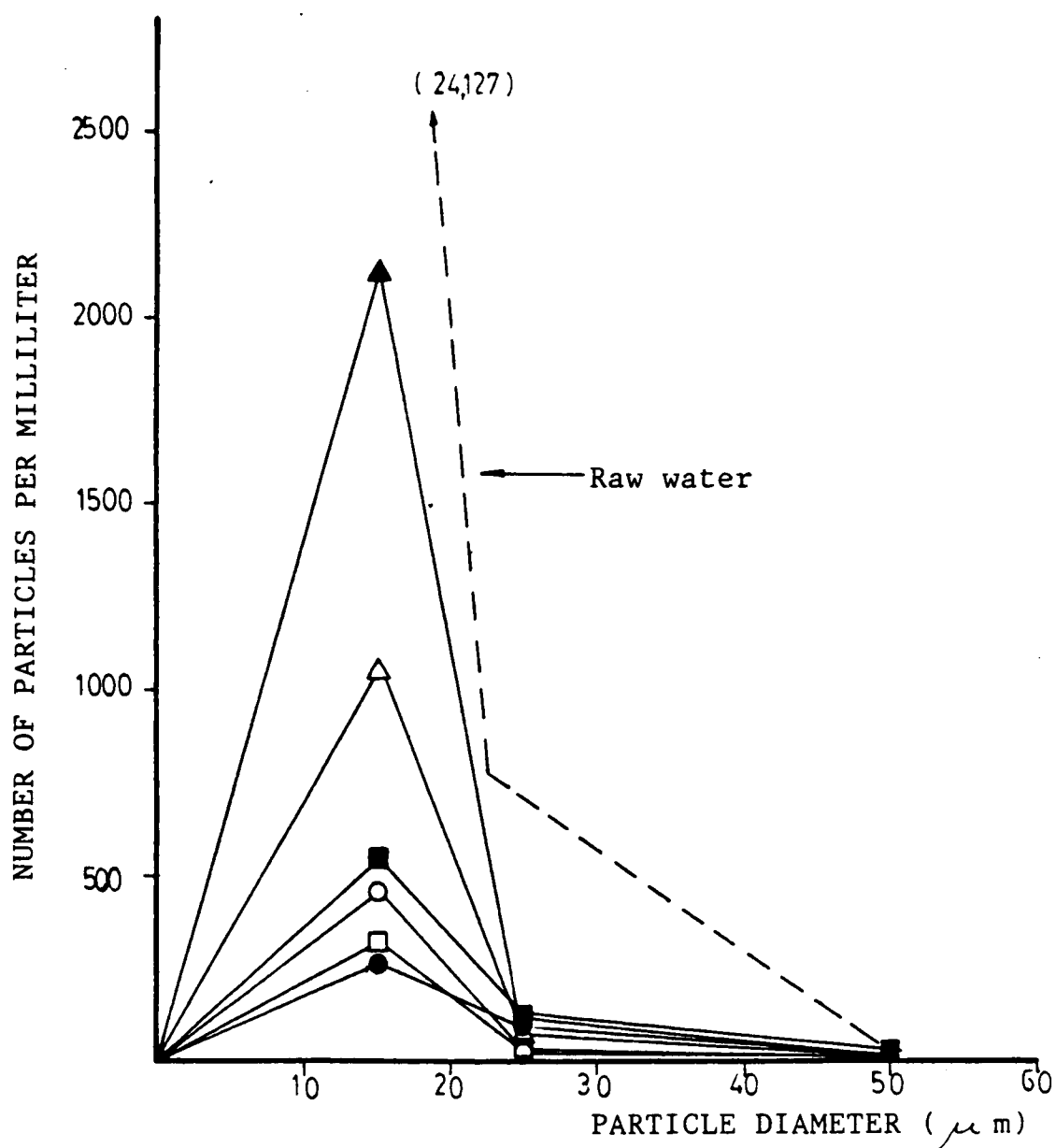
Figure 5-5. Settling Curves from Jar-Test No. 6 Data.

Table 5-7. Particle Size Distribution in Supernatant for Jar Test No. 2.

Range (μm)	d (μm)	Test Number						
		19	20	21	22	23	24	Raw
10-20	15	455	274	327	547	1055	2138	24127
20-30	25	27	80	35	137	58	59	770
30-70	50	1	12	1	13	6	4	20
N		483	366	363	697	1119	2201	24917

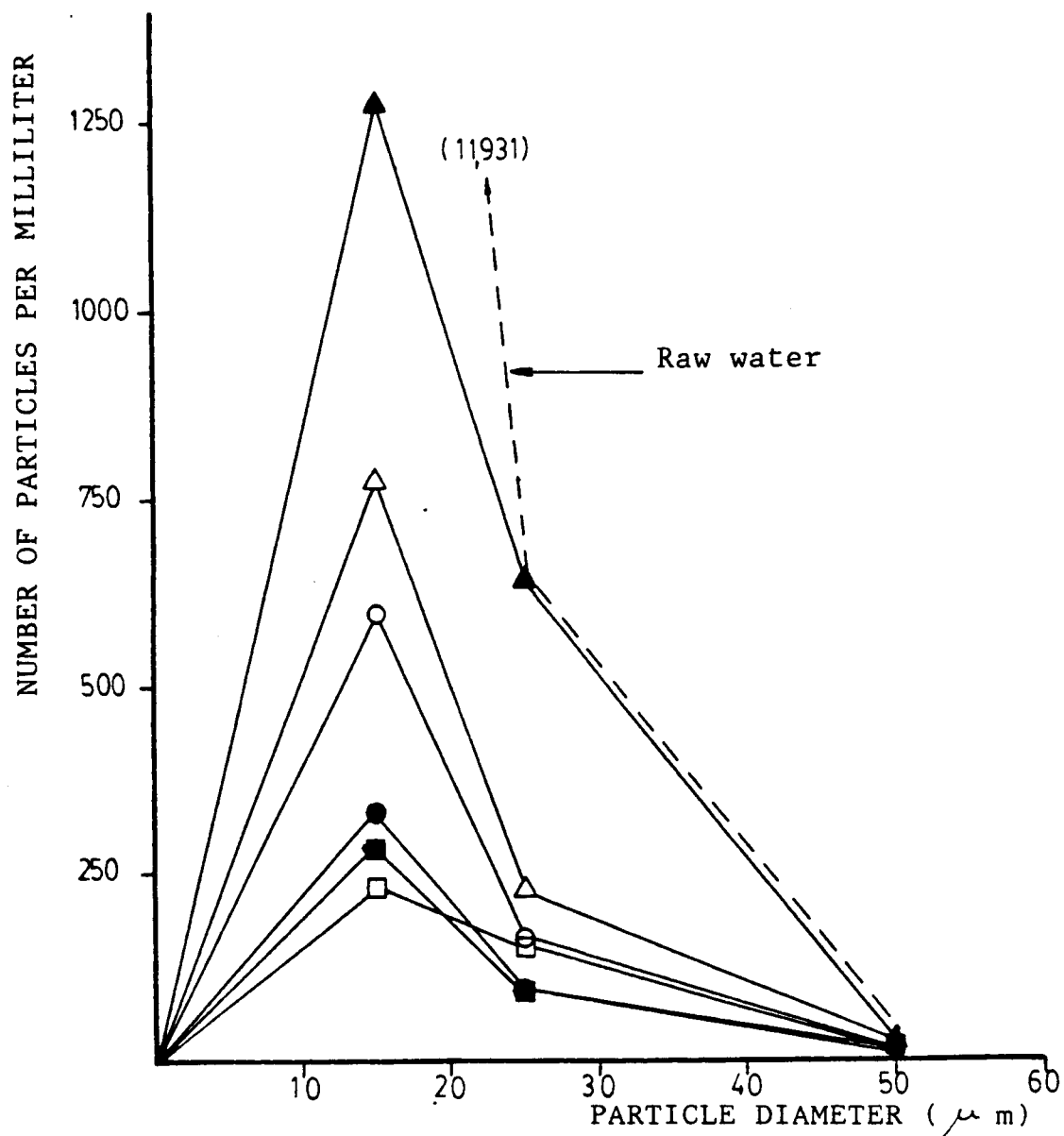
Table 5-8. Particle Size Distribution in Supernatant for Jar Test No. 6.

Range (μm)	d (μm)	Test Number						Raw
		43	44	45	46	47	48	
10-20	15	598	332	232	287	776	1277	11931
20-30	25	164	97	154	97	230	643	652
30-70	50	23	17	24	18	22	34	51
N		785	446	410	402	1028	1954	12634



Data from jar test #2. Dosage (mg/L): 10 (○—○); 15 (●—●); 20 (□—□); 25 (■—■); 30 (△—△); 35 (▲—▲). Series number: 19 to 24.

Figure 5-6. Particle Size Distribution from Jar-Test No. 2 Using the HIAC Particle Counter.



Data from jar test #6. Dosage (mg/L): 10 (○—○);
 15 (●—●); 20 (□—□); 25 (■—■); 30 (△—△) ;
 35 (▲—▲). Series number: 43 to 48.

Figure 5-7. Particle Size Distribution from Jar-Test No. 6
 Using the HIAC Particle Counter.

in Figures 5-8 and 5-9, showing the number of particles versus alum dosage for the lower range of particles (10 to 70 μm) and mean diameter versus alum dosage for the particle range 75 to 900 μm .

The computer program COVT was fed with the particle counts and size data obtained from the jar-tests and measured photographically and by using the HIAC particle counter. Ten ranges of particles were analyzed. The first range gathered together all the particles in the range 10 to 70 μm . To this range, a diameter of 15 μm was assigned, because that diameter corresponded to the mean diameter of the particles in that range, as shown previously. The other nine ranges were fed with the data obtained photographically.

The particle density was assumed to be constant and equal to 1002 Kg/m^3 . The water density and viscosity were taken from text book values for the temperature of the samples. Figure 5-10 shows a plot of the concentration of floc particles at the end of the flocculation process (just after the mixing system was shut off), $C(0)$, versus alum dosage. A summary of these data is shown in Table 5-9. Figures 5-11 and 5-12 show plots of the ratio of concentration $C(t)/C(0)$ versus time t for two different tests. From these figures it can be seen that, for those samples with the optimum dosage, $C(t)/C(0)$ decreases at a faster rate.

A relationship between turbidity and ratio of concentration $C(t)/C(0)$ was also determined in this study. This relationship showed that particle size distribution in any particular size range can be used as a predictor of optimum chemical dosage. Values of $C(t)/C(0)$ were plotted versus standardized turbidity. Given the relatively

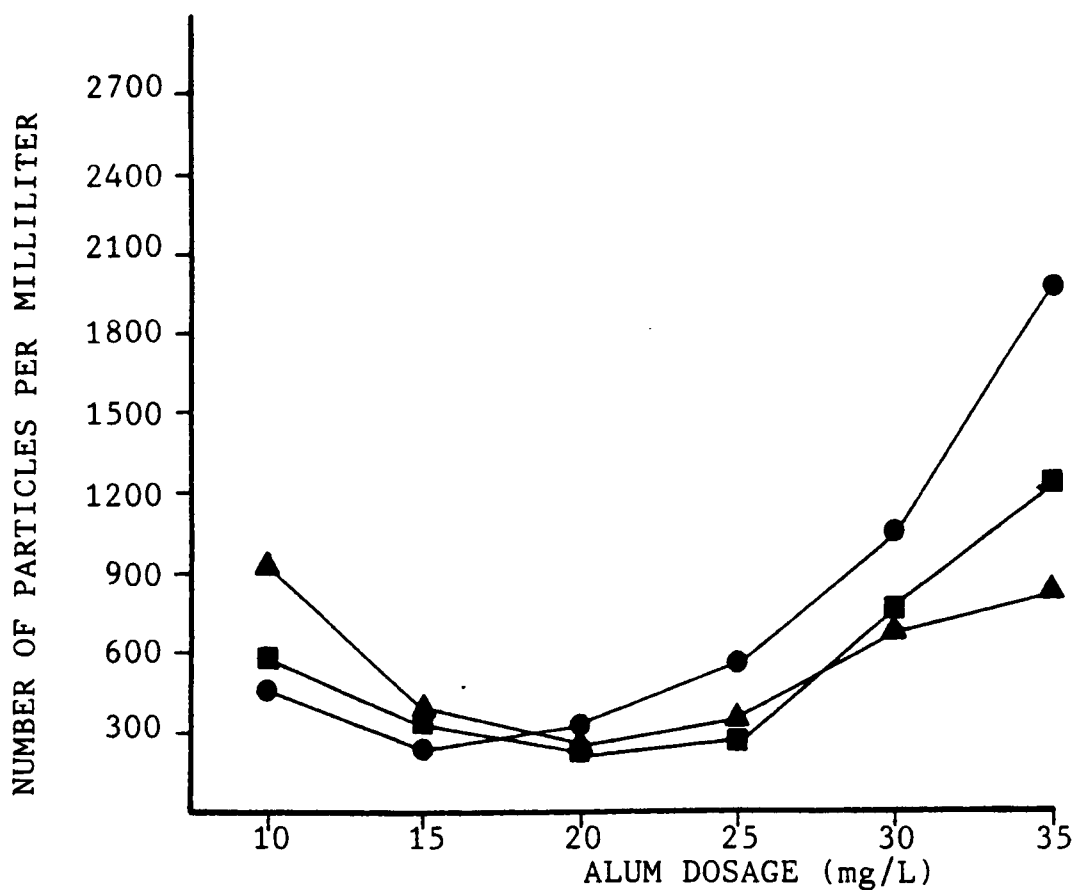


Figure 5-8. Effect of Alum Dosage on Number of Particles in Supernatant.

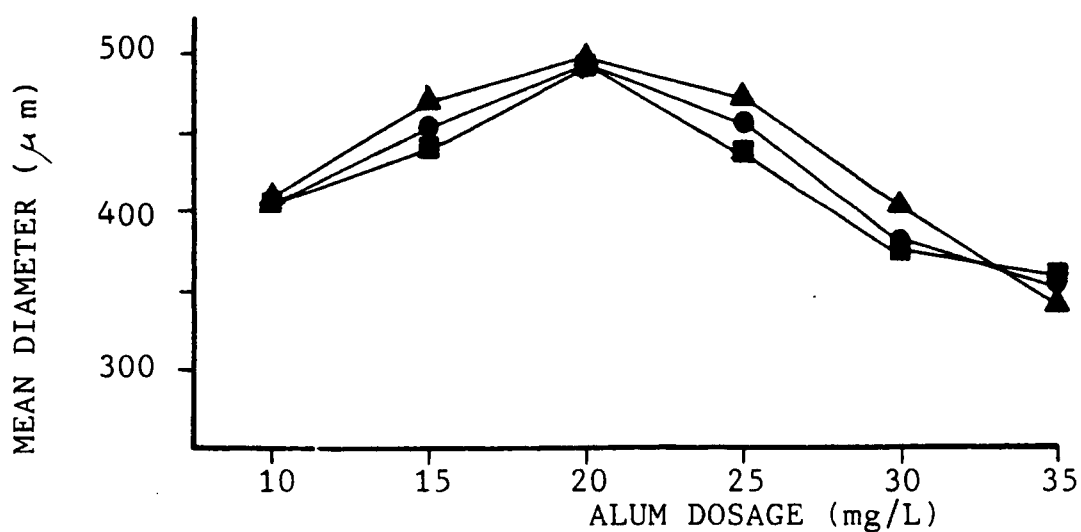
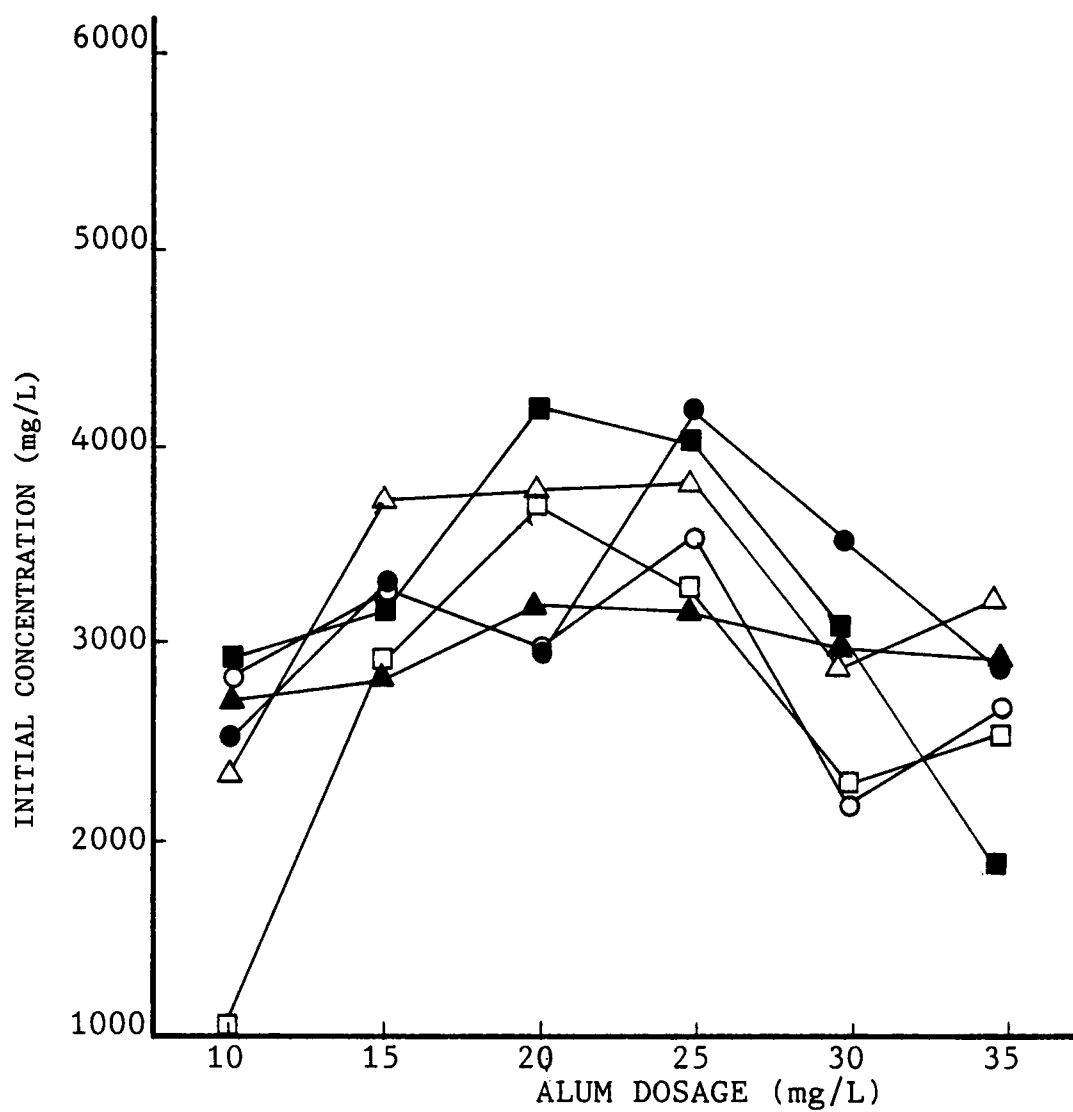


Figure 5-9. Effect of Alum Dosage on Particle Mean Diameter.



Dosage (mg/L): 10 (○); 15 (●); 20 (□);
25 (■); 30 (△); 35 (▲).

Figure 5-10. Effect of the Alum Dosage on the Initial Concentration.

Table 5-9. Floc Initial Concentration.

Dosage (mg/L) Jar-Test	10 - - - - -	15 - - - - -	20 C(0)	25 (mg/L)	30 - - - - -	35 - - - - -
1	3282	3843	3478	4186	2452	3110
2	2905	3941	3446	5003	4184	3382
3	1049	3435	4406	3885	2623	2956
4	3408	4225	5072	4800	3635	2121
5	2663	2663	4448	4543	3367	3868
6	3146	3329	3769	3651	3039	2961

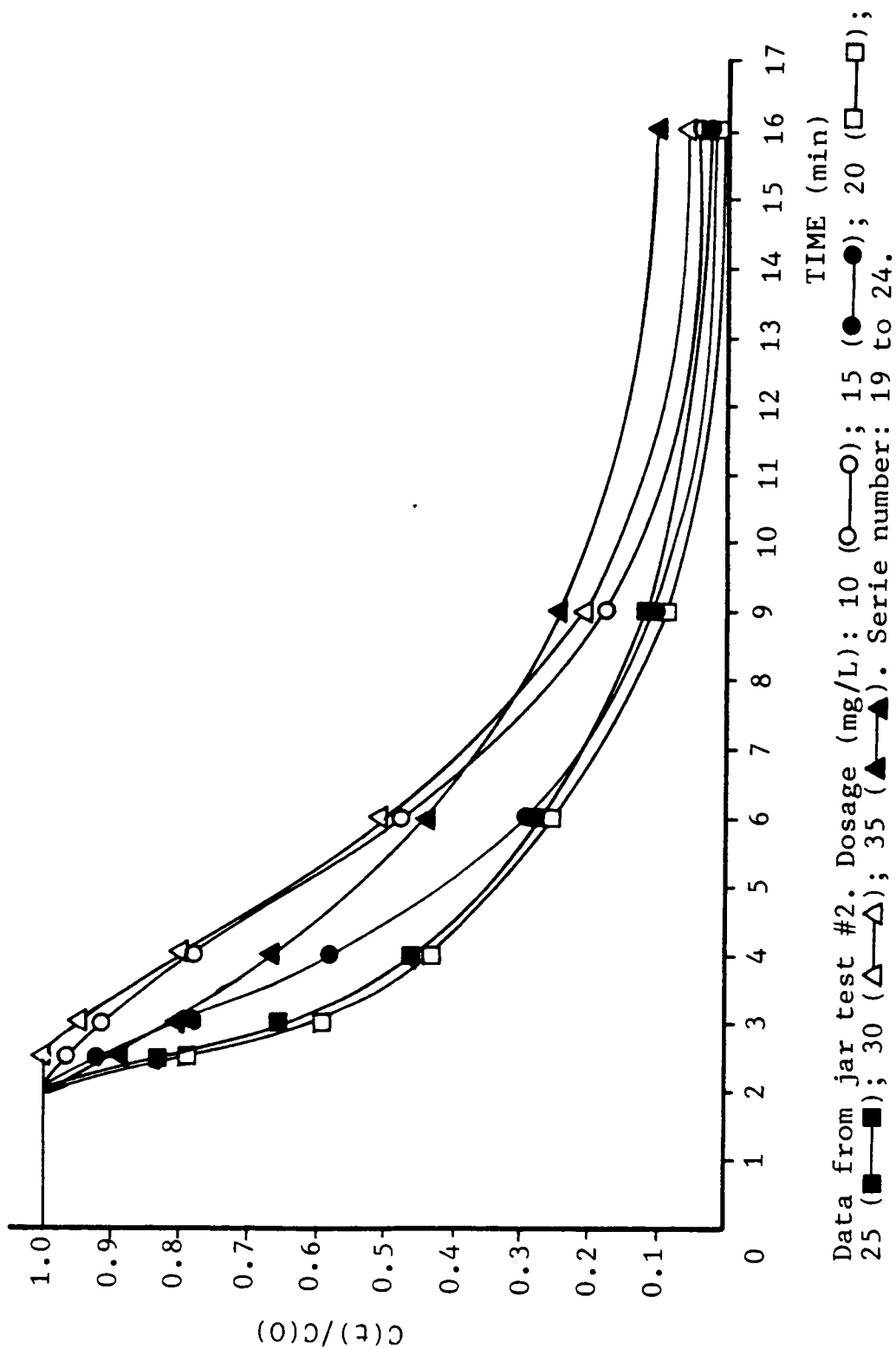
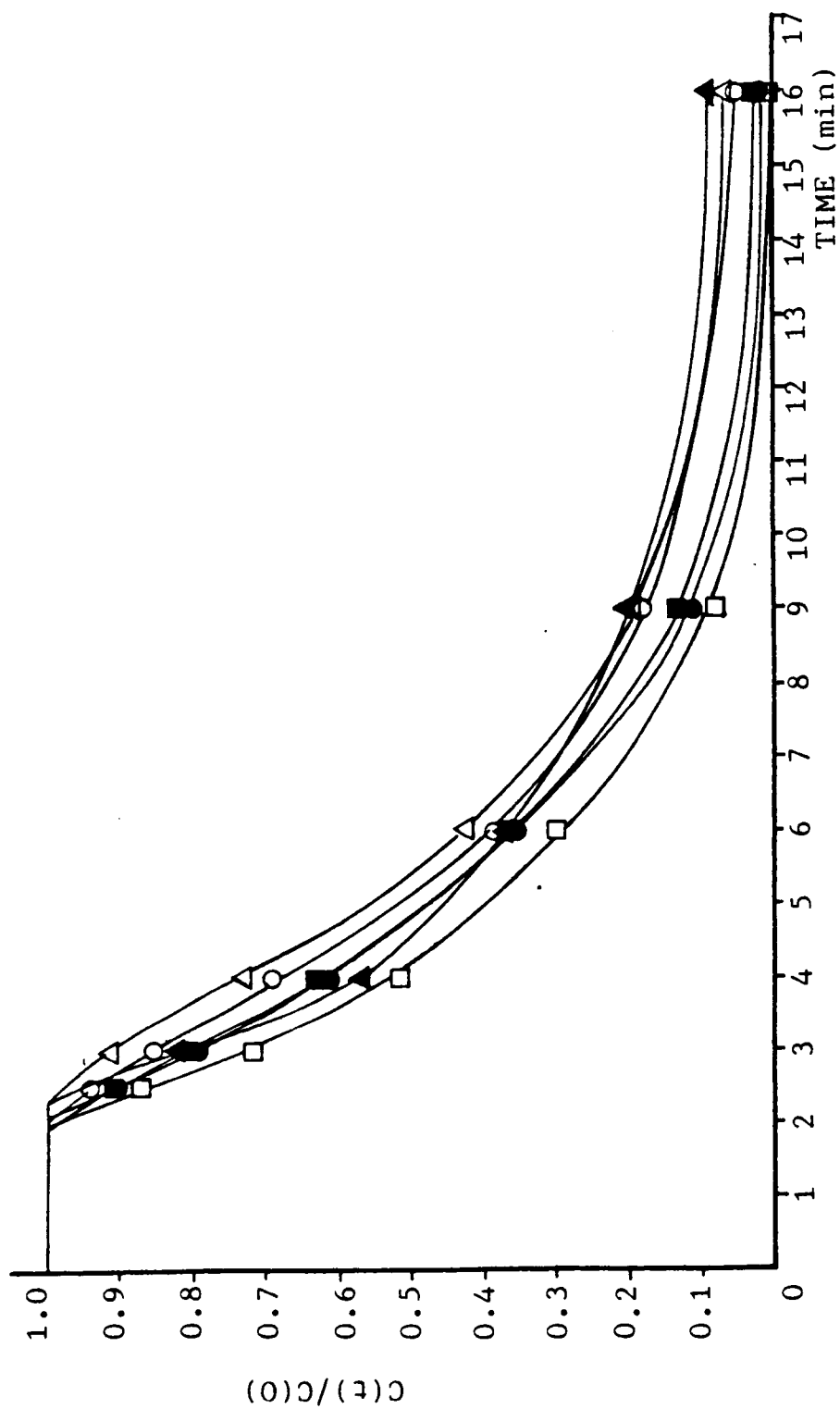


Figure 5-11. Concentration Ratio Curves From Jar-Test No. 2 for Computer Program COVT Data.

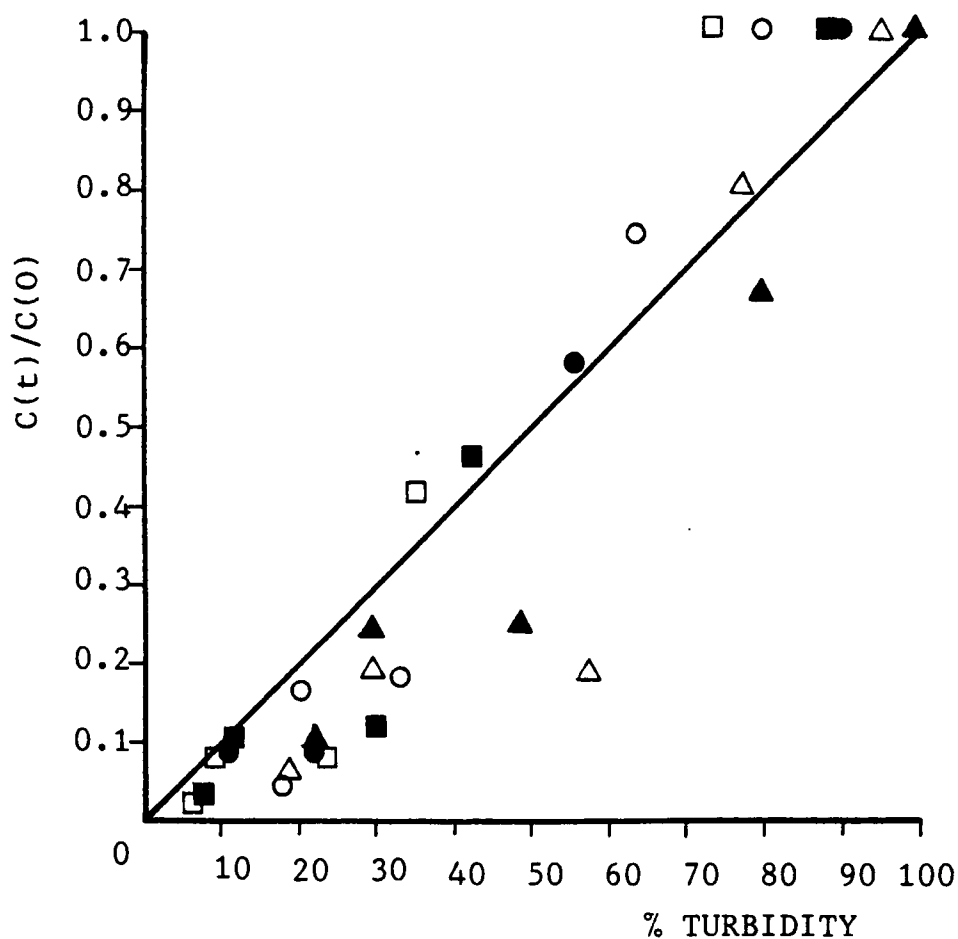


Data from jar test #6. Dosage (mg/L): 10 (O—O); 15 (●—●); 20 (□—□); 25 (■—■); 30 (△—△); 35 (▲—▲). Series number: 43 to 48.

Figure 5-12. Concentration Ratio Curves From Jar-Test No. 6 for Computer Program COVT Data.

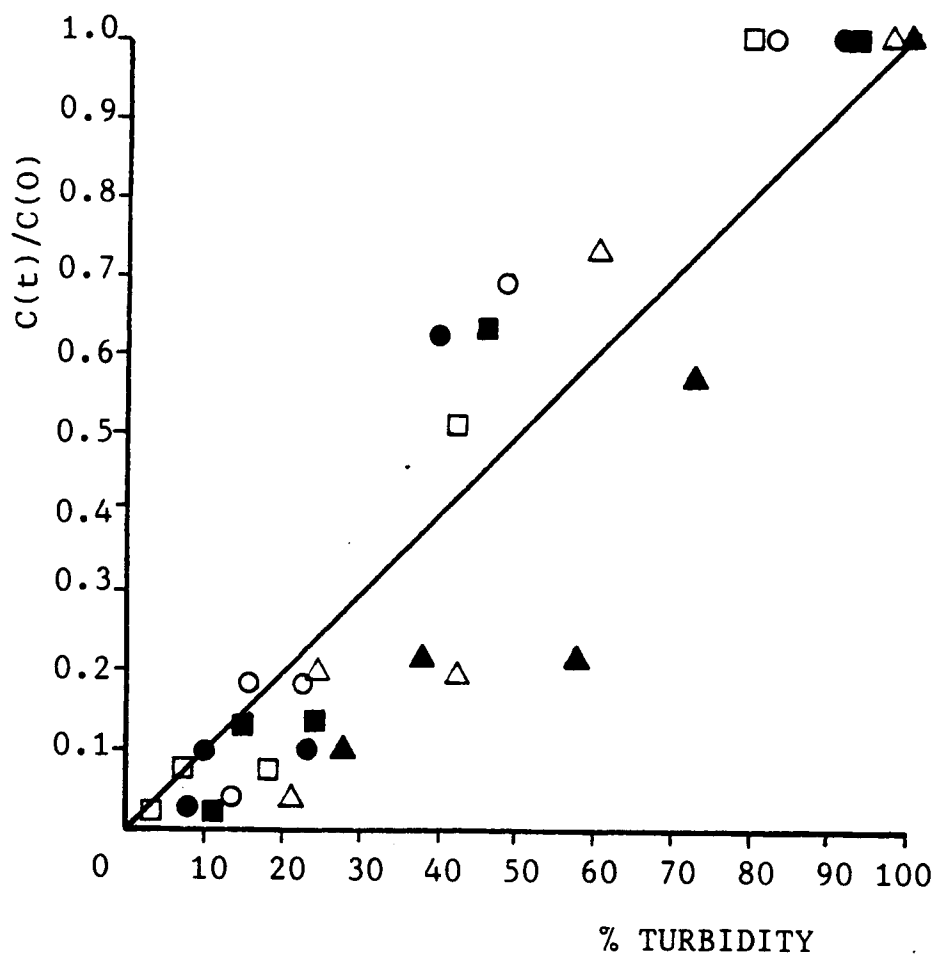
narrow range of sizes and concentrations, a direct relationship between $C(t)/C(0)$ and turbidity could be assumed for comparative purposes with the line formed by the data forming a 45° angle to the horizontal and passing through the origin. A non-linear pattern would have been expected from a water with a wider range of particle sizes. The data follow a pattern which is generally very close to a straight line indicating a good agreement of the predicted to measured data. This can be seen in Figures 5-13 and 5-14. These data are summarized in Tables 5-10 and 5-11.

Another relationship between $C(t)/C(0)$ and turbidity was determined to show that the analysis of particle size can be used to determine the optimum alum dosage. Based on the remaining turbidity for six series of jar-tests, a rank from 1 to 6 was assigned to each sample. Number one was assigned to the optimum dosage that results in the lowest supernatant turbidity, and number six to the sample with highest supernatant turbidity. These can be seen in Table 5-12. The same idea was used to assign a rank to the samples based on the dimensionless concentration $C(t)/C(0)$. A summary of these data is shown in Table 5-13. In general, it can be said that there is a coincidence in the ranks for the best dosage, and also for the worst one.



Data from jar test #2. Dosage (mg/L): 10 (○—○);
 15 (●—●); 20 (□—□); 25 (■—■); 30 (△—△);
 35 (▲—▲). Serie number: 19 to 24.

Figure 5-13. Comparison of Concentration Ratio $C(t)/C(0)$ and the Residual Turbidity for Jar-Test No. 2.



Data from jar test #6. Dosage (mg/L): 10 (○—○); 15 (●—●); 20 (□—□); 25 (■—■); 30 (△—△); 35 (▲—▲). Serie number: 43 to 48.

Figure 5-14. Comparison of Concentration Ratio $C(t)/C(0)$ and the Residual Turbidity for Jar-Test No. 6.

Table 5-10. Summary of Concentration Ratio and Turbidity for Jar Test No. 2.

Test Number											
19			20			21			22		
t (min)	Ct/Co	turb (NTU)	Ct/Co	turb (NTU)	turb (NTU)	Ct/Co	turb (NTU)	turb (NTU)	Ct/Co	turb (NTU)	turb (NTU)
0	1.0	21.0	1.0	23.0	1.0	20.0	1.0	23.0	1.0	24.0	25.0
2	1.0	20.0	1.0	22.5	1.0	18.5	1.0	22.0	1.0	24.0	24.5
5	0.79	16.0	0.58	14.0	0.43	9.0	0.47	10.5	0.80	19.5	20.0
10	0.18	8.5	0.10	6.3	0.09	6.0	0.12	7.4	0.20	14.5	12.0
15	0.18	5.5	0.10	3.1	0.09	2.7	0.12	3.5	0.20	7.3	7.5
20	0.05	4.5	0.03	1.7	0.02	1.2	0.03	2.0	0.06	4.8	6.3

Table 5-11. Summary of Concentration Ratio and Turbidity for Jar Test No. 6.

t (min)	Test Number											
	43	44	45	46	47	48	43	44	45	46	47	48
	Ct/Co	turb (NTU)	Ct/Co	turb (NTU)	Ct/Co	turb (NTU)	Ct/Co	turb (NTU)	Ct/Co	turb (NTU)	Ct/Co	turb (NTU)
0	1.0	24.0	1.0	24.5	1.0	22.0	1.0	24.0	1.0	24.5	1.0	25.0
2	1.0	20.5	1.0	22.5	1.0	20.0	1.0	23.0	1.0	24.0	1.0	24.5
5	0.69	12.0	0.62	9.9	0.51	10.5	0.63	11.5	0.73	15.0	0.57	18.0
10	0.18	5.5	0.10	5.9	0.08	4.4	0.13	5.7	0.18	10.5	0.21	14.5
15	0.18	3.75	0.10	2.5	0.08	2.0	0.13	3.5	0.18	5.8	0.21	9.4
20	0.05	3.4	0.03	2.0	0.01	1.0	0.03	2.9	0.06	5.2	0.10	6.8

Table 5-12. Ranking Function of Turbidity.

Dosage (mg/L) Jar Test	10	15	20	25	30	35
	Rank					
1	4	3	1	2	5	6
2	4	2	1	3	5	6
3	6	2	1	3	4	5
4	5	3	1	2	4	6
5	5	3	1	2	4	6
6	4	2	1	3	5	6
Final Rank	5	2	1	2	4	6

Table 5-13. Ranking Function of $C(t)/C(0)$.

Dosage (mg/L) Jar Test	10	15	20	25	30	35
	Rank					
1	4	3	1	2	6	5
2	4	3	1	2	5	6
3	6	3	2	1	4	5
4	4	2	1	3	5	6
5	5	3	1	2	4	6
6	4	2	1	3	5	6
Final Rank	4	3	1	2	5	6

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

The evidence from this research clearly shows that the characteristics of the particle size distribution is one of the principal parameters in the optimization of the coagulation and flocculation process. Particles with a large mean diameter led to significantly more rapid settling velocities.

In these experiments it was found that the number of colloidal particles in the raw-water were significantly reduced as the particles agglomerated, a reduction that had a minimum around the optimum dosage. It was also shown that optimum dosage produced a normal distribution with a large mean diameter. For those samples dosed away from the optimum dosage, the distribution was skewed with a smaller mean diameter. This fact indicated that knowing the particle size distribution in the suspension would make it possible to know if the dosage is at optimum. This could be determined by simply knowing if the distribution is normal or if it is skewed. Also an analysis of the number of floc particles at the end of the settling basin can give valuable information. It was shown that the number of small particles after the settling period was reduced to a minimum when the alum dosage was at the optimum.

The results obtained also show a relationship between the optimum alum dosage and the concentration of floc particles in the

suspension which are in turn related to the size of the particles involved. The initial concentration of floc particles in the suspension was found to be maximum for the optimum dosage. It was also found that for the optimum dosage the ratio of concentration $C(t)/C(0)$, decreased with time at a faster rate indicating higher net settling velocities. This fact may also be used to predict the optimum alum dosage in the coagulation process.

There is no simple and direct relationship between the number, size, and size distribution in suspension and their turbidity, but this study indicated that it is possible to closely predict the remaining turbidity assuming a direct relationship with the ratio of concentration $C(t)/C(0)$.

Because particle concentration and particle size distribution have a direct effect on the performance of coagulation and sedimentation processes and on the overall plant performance, these characteristics should be considered in the design and operation of water treatment plants. It is evident that new control techniques have to be developed. Although photograph techniques and an electronic particle counter were used in this research, it is obvious they cannot be used for a day-by-day control of water treatment plants. Particle counters, apart from the high cost, present several disadvantages, such as limitation of particle size range, coincidence, and particle breakup during the sampling period.

It is necessary to remark that the use of an electronic particle counter may lead to erroneous conclusions if used to analyze floc particle size. This research showed that floc particles were severely

broken in their pass through the analyzer. A sample that had a mean diameter of 445 μm , using the photographic method was found to have a mean diameter eleven times smaller using the HIAC particle counter.

It would appear from this research that the development of an in situ device to sense relative size distribution would enhance the control of coagulation/flocculation units.

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APPENDIXES

APPENDIX A
SUMMARY OF EXPERIMENTAL DATA

SUMMARY OF EXPERIMENTAL DATA

Table A-1. Particle Size Distribution for Jar Test No. 1.

Alum Dosage (mg/L)		10	15	20	25	30	35
Range	d	Test Number					
(μm)	(μm)	13	14	15	16	17	18
75-125	100	12	8	2	7	18	23
125-200	162.5	21	10	3	11	25	34
200-300	250	28	22	8	19	30	37
300-400	350	31	23	14	26	32	27
400-500	450	25	21	22	22	22	22
500-600	550	16	14	11	19	8	13
600-700	650	5	7	6	7	4	7
700-800	750	1	4	4	3	0	1
800-900	850	0	1	2	1	0	0
N		139	110	72	115	139	164
$\bar{d}_{10}$		337	377	441	389	302	300
$\bar{d}_{20}$		369	414	470	423	334	337
$\bar{d}_{30}$		397	447	495	453	363	370
$\sigma^2 \cdot 10^{-4}$		2.27	2.90	2.70	2.74	1.98	2.43
$m_3 \cdot 10^{-6}$		1.09	2.02	1.21	1.22	1.25	0.25
$m_4 \cdot 10^{-9}$		1.20	2.40	2.22	1.93	0.99	1.54
K		2.36	2.62	2.93	2.57	2.52	2.62
S		0.32	0.40	0.27	0.27	0.45	0.66

Table A-2. Particle Size Distribution for Jar Test No. 3.

Alum Dosage (mg/L)		10	15	20	25	30	35
Range	d	- - - - - Test Number - - - - -					
(μm)	(μm)	25	26	27	28	29	30
75-125	100	15	6	3	8	11	18
125-200	165.2	17	10	6	12	24	31
200-300	250	27	13	20	16	26	34
300-400	350	20	20	27	18	29	35
400-500	450	10	22	29	34	23	15
500-600	550	2	11	12	15	7	8
600-700	650	1	6	6	4	5	6
700-800	750	0	3	3	2	1	3
800-900	850	0	1	4	2	0	0
N		92	92	110	111	126	150
$\bar{d}_{10}$		267	388	407	384	319	301
$\bar{d}_{20}$		293	424	439	418	352	336
$\bar{d}_{30}$		317	456	469	446	381	371
$\sigma^2 \cdot 10^{-4}$		1.47	2.85	2.70	2.72	2.13	2.37
$m_3 \cdot 10^{-6}$		1.03	1.50	2.99	1.15	1.65	3.21
$m_4 \cdot 10^{-9}$		0.65	2.18	2.50	2.19	1.25	1.90
K		3.02	2.69	3.14	2.95	2.77	3.38
S		0.58	0.31	0.67	0.26	0.53	0.88

Table A-3. Particle Size Distribution for Jar Test No. 4.

Alum Dosage (mg/L)		10	15	20	25	30	35
Range	d	Test Number					
(μm)	(μm)	31	32	33	34	35	36
75-125	100	14	6	4	7	15	24
125-200	162.5	17	12	7	8	23	30
200-300	250	21	10	12	22	30	28
300-400	350	30	21	27	23	26	32
400-500	450	27	24	18	26	24	22
500-600	550	16	16	15	13	20	8
600-700	650	5	10	10	9	6	2
700-800	750	1	4	6	5	1	0
800-900	850	1	1	3	3	0	0
N		132	104	102	116	145	146
$\bar{d}_{10}$		347	406	430	400	337	284
$\bar{d}_{20}$		381	441	466	438	373	315
$\bar{d}_{30}$		410	470	498	472	403	342
$\sigma^2 \cdot 10^{-4}$		2.56	3.03	3.24	3.20	2.52	1.90
$m_3 \cdot 10^{-6}$		1.28	0.57	1.93	2.53	1.29	1.16
$m_4 \cdot 10^{-9}$		1.75	2.20	2.67	2.81	1.30	0.86
K		2.68	2.40	2.55	2.72	2.16	2.36
S		0.31	0.11	0.33	0.44	0.32	0.44

Table A-4. Particle Size Distribution for Jar Test No. 5.

Alum Dosage (mg/L)		10	15	20	25	30	35
Range	d	Test Number					
(μm)	(μm)	37	38	39	40	41	42
75-125	100	12	8	3	6	16	32
125-200	162.5	14	9	4	10	22	44
200-300	250	28	14	6	12	26	49
300-400	350	23	19	22	22	28	36
400-500	450	22	28	24	25	21	22
500-600	550	12	15	16	14	14	10
600-700	650	4	8	8	6	8	6
700-800	750	1	4	6	6	2	3
800-900	850	0	2	1	2	0	2
N		116	107	90	103	137	204
$\bar{d}_{10}$		333	406	451	411	331	288
$\bar{d}_{20}$		366	442	478	449	369	328
$\bar{d}_{30}$		394	473	502	481	402	367
$\sigma^2 * 10^{-4}$		2.28	3.12	2.57	3.16	2.70	2.56
$m_3 * 10^{-6}$		1.21	1.12	3.97	1.74	2.00	4.51
$m_4 * 10^{-9}$		1.27	2.56	1.87	2.67	1.74	2.67
K		2.44	2.63	2.84	2.68	2.38	4.07
S		0.35	0.20	0.10	0.31	0.45	1.10

Table A-5. Jar Test No. 1 Results.

Parameter	13	14	15	16	17	18
Rapid Mix						
rpm	100	100	100	100	100	100
min	2	2	2	2	2	2
Alum Dosage (mg/L)	10	15	20	25	30	35
Flocculation						
rpm	50	50	50	50	50	50
min	20	20	20	20	20	20
Turbidity (NTU)						
after: 0 min	23.0	22.0	19.0	20.0	22.0	24.0
1 min	23.0	21.0	18.0	19.0	21.0	24.0
2 min	22.0	20.0	16.5	18.5	20.5	23.0
5 min	14.5	10.5	9.8	12.5	17.5	19.5
10 min	8.8	6.3	5.7	5.4	10.5	12.5
15 min	4.9	3.1	2.0	2.7	5.7	6.3
20 min	3.5	2.1	1.1	1.7	4.3	4.7
pH	7.6	7.4	7.2	7.1	7.0	6.9

Table A-6. Jar Test No. 3 Results.

Parameter		Test Number					
		25	26	27	28	29	30
Rapid Mix							
rpm		100	100	100	100	100	100
min		2	2	2	2	2	2
Alum Dosage (mg/L)		10	15	20	25	30	35
Flocculation							
rpm		50	50	50	50	50	50
min		20	20	20	20	20	20
Turbidity (NTU)							
After:	0 min	28.0	27.0	25.0	27.0	28.0	30.0
	1 min	28.0	27.5	24.5	26.5	28.0	30.0
	2 min	28.0	26.0	24.0	26.5	28.0	30.0
	5 min	24.0	17.5	14.5	19.0	20.5	18.0
	10 min	14.0	8.5	6.5	7.9	10.5	11.5
	15 min	9.0	4.7	3.8	4.3	7.2	7.8
	20 min	5.1	2.3	1.5	2.5	3.6	4.4
pH		7.7	7.4	7.3	7.2	7.0	6.9

Table A-7. Jar Test No. 4 Results.

Parameter		31	32	33	34	35	36
Rapid Mix							
rpm		100	100	100	100	100	100
min		2	2	2	2	2	2
Alum Dosage (mg/L)		10	15	20	25	30	35
Flocculation							
rpm		50	50	50	50	50	50
min		20	20	20	20	20	20
Turbidity (NTU)							
After:	0 min	24.0	24.0	23.0	23.0	24.0	24.5
	1 min	24.0	24.0	22.5	23.0	24.0	24.0
	2 min	24.0	23.5	22.0	22.5	24.0	24.0
	5 min	18.5	15.0	11.3	14.5	19.5	20.0
	10 min	11.0	8.2	7.6	9.4	10.0	17.5
	15 min	7.5	4.1	3.0	5.1	6.6	13.0
	20 min	5.8	2.7	1.9	2.4	5.3	6.2
pH		7.7	7.6	7.4	7.1	7.1	7.0

Table A-8. Jar Test No. 5 Results.

Parameter		- - - - -	- - - - -	- - - - -	Test Number	- - - - -	- - - - -
		37	38	39	40	41	42
Rapid Mix							
rpm		100	100	100	100	100	100
min		2	2	2	2	2	2
Alum Dosage (mg/L)		10	15	20	25	30	35
Flocculation							
rpm		50	50	50	50	50	50
min		20	20	20	20	20	20
Turbidity (NTU)							
After	0 min	21.0	19.0	18.0	20.0	20.0	22.0
	1 min	21.0	19.0	17.5	19.0	20.0	22.5
	2 min	20.5	18.5	17.0	18.5	20.0	21.0
	5 min	16.0	12.5	9.5	11.3	17.5	18.0
	10 min	8.2	7.5	7.3	7.0	9.8	11.5
	15 min	4.9	3.4	2.8	2.8	3.3	6.3
	20 min	3.0	2.2	1.6	2.0	2.7	4.5
pH		7.5	7.6	7.3	7.0	7.0	7.0

Table A-9. Particle Size Distribution in Supernatant for Jar Test No. 1.

Range (μm)	d (μm)	- - - - - 13	- - - - - 14	- - - - - 15	Test Number 16	- - - - - 17	- - - - - 18	- - - - - Raw
10-20	15	479	295	153	520	725	1245	21497
20-30	25	84	74	63	97	80	140	1119
30-70	50	23	14	6	19	34	24	88
N		586	383	222	636	839	1409	22704

Table A-10. Particle Size Distribution in Supernatant for Jar Test No. 3.

Range (μm)	d (μm)	- - - - - 25	- - - - - 26	- - - - - 27	Test Number 28	- - - - - 29	- - - - - 30	- - - - - Raw
10-20	15	300	204	153	221	312	450	14650
20-30	25	46	30	6	65	26	69	638
30-70	50	20	13	1	18	4	5	24
N		366	247	160	304	342	524	15312

Table A-11. Particle Size Distribution in Supernatant for Jar Test No. 4.

Range (μm)	d (μm)	Test Number						Raw
		31	32	33	34	35	36	
10-20	15	924	380	226	502	683	843	17276
20-30	25	112	162	47	103	100	169	803
30-70	50	10	46	5	9	7	25	65
N		1046	588	278	614	790	1037	18144

Table A-12. Particle Size Distribution in Supernatant for Jar Test No. 5.

Range (μm)	d (μm)	Test Number						Raw
		37	38	39	40	41	42	
10-20	15	886	148	152	699	687	776	18997
20-30	25	108	55	41	191	136	143	813
30-70	50	10	18	9	15	7	5	30
N		1004	221	202	905	830	934	19840

Table A-13. Summary of Concentration Ratio and Turbidity for Jar Test No. 1.

		Test Number											
		13		14		15		16		17		18	
t (min)	Ct/Co	turb (NTU)	Ct/Co	turb (NTU)	Ct/Co	turb (NTU)	Ct/Co	turb (NTU)	Ct/Co	turb (NTU)	Ct/Co	turb (NTU)	Ct/Co
0	1.0	23.0	1.0	22.0	1.0	19.0	1.0	20.0	1.0	22.0	1.0	24.0	1.0
2	1.0	22.0	1.0	20.0	1.0	16.5	1.0	18.5	1.0	20.5	1.0	23.0	1.0
5	0.76	14.5	0.54	10.5	0.49	9.8	0.59	12.5	0.78	17.5	0.72	19.5	0.72
10	0.19	8.8	0.12	6.3	0.07	5.7	0.12	5.4	0.26	10.5	0.20	12.5	0.20
15	0.19	4.9	0.12	3.1	0.07	2.0	0.12	2.7	0.26	5.7	0.20	6.3	0.20
20	0.05	3.5	0.03	2.1	0.01	1.1	0.03	1.7	0.08	4.3	0.08	4.8	0.08

Table A-14. Summary of Concentration Ratio and Turbidity for Jar Test No. 3.

		Test Number																	
		25			26			27			28			29			30		
t	(min)	Ct/Co	turb (NTU)	Ct/Co	turb (NTU)	Ct/Co	turb (NTU)	Ct/Co	turb (NTU)	Ct/Co	turb (NTU)	Ct/Co	turb (NTU)	Ct/Co	turb (NTU)	Ct/Co	turb (NTU)		
0		1.0	28.0	1.0	27.0	1.0	25.0	1.0	27.0	1.0	28.0	1.0	27.0	1.0	28.0	1.0	30.0		
2		1.0	28.0	1.0	26.0	1.0	24.0	1.0	26.5	1.0	28.0	1.0	28.0	1.0	28.0	1.0	30.0		
5		0.88	24.0	0.53	17.5	0.50	14.5	0.64	19.0	0.70	20.5	0.59	18.0	0.59	18.0	0.59	18.0		
10		0.43	14.0	0.11	8.5	0.11	6.1	0.09	7.9	0.22	10.5	0.25	11.5	0.25	11.5	0.25	11.5		
15		0.43	9.0	0.11	4.7	0.11	3.8	0.09	4.3	0.22	7.2	0.25	7.8	0.25	7.8	0.25	7.8		
20		0.16	5.1	0.02	2.3	0.02	1.5	0.03	2.5	0.06	3.6	0.07	4.4	0.07	4.4	0.07	4.4		

Table A-15. Summary of Concentration Ratio and Turbidity for Jar Test No. 4.

Test Number										
31		32		33		34		35		36
t (min)	Ct/Co	turb (NTU)	Ct/Co	turb (NTU)	Ct/Co	turb (NTU)	Ct/Co	turb (NTU)	Ct/Co	turb (NTU)
0	1.0	24.0	1.0	24.0	1.0	23.0	1.0	23.0	1.0	24.0
2	1.0	24.0	1.0	23.5	1.0	22.0	1.0	22.5	1.0	24.0
5	0.73	18.5	0.53	15.0	0.40	11.3	0.66	14.5	0.75	19.5
10	0.16	11.0	0.09	8.2	0.08	7.6	0.09	9.4	0.16	10.0
15	0.16	7.5	0.09	4.1	0.08	3.0	0.09	5.1	0.16	6.6
20	0.04	5.8	0.02	2.7	0.01	1.9	0.03	2.4	0.05	5.3
										6.2

Table A-16. Summary of Concentration Ratio and Turbidity for Jar Test No. 5.

t (min)	Test Number											
	37		38		39		40		41		42	
	Ct/Co	turb (NTU)	Ct/Co	turb (NTU)	Ct/Co	turb (NTU)	Ct/Co	turb (NTU)	Ct/Co	turb (NTU)	Ct/Co	turb (NTU)
0	1.0	21.0	1.0	19.0	1.0	18.0	1.0	20.0	1.0	20.0	1.0	22.0
2	1.0	20.5	1.0	18.5	1.0	17.0	1.0	18.5	1.0	20.0	1.0	21.0
5	0.75	16.0	0.51	12.5	0.49	9.5	0.47	11.3	0.64	17.5	0.58	18.0
10	0.19	8.2	0.08	7.5	0.08	7.3	0.09	7.0	0.17	9.8	0.22	11.5
15	0.19	4.9	0.08	3.4	0.08	2.8	0.09	2.8	0.17	3.3	0.22	6.3
20	0.06	3.0	0.02	2.2	0.01	1.6	0.02	2.0	0.05	2.7	0.08	4.5

APPENDIX B
COMPUTER PROGRAM COVT

COMPUTER PROGRAM COVT

```
100  REM PROGRAM COVT
110  PRINT "NUMBER OF CHANNELS:";
120  INPUT N
130  PRINT "GIVE THE UPPER SIZE OF EACH CHANNEL"
140  FOR I = 1 TO N
150  PRINT "SIZE OF CHANNEL No. ",I,"(MICRONS):";
160  INPUT D(I)
170  NEXT I
180  FOR I = 1 TO N
190  PRINT "No. OF PART. IN CHANNEL",I," (#/mL): ";
200  INPUT NP(I)
210  NEXT I
220  PRINT "WATER DENSITY (Kg/m^3): ";
230  INPUT WDENS
240  PRINT "FLOC DENSITY (Kg/M^3): ";
250  INPUT PDENS
260  PRINT "DYNAMIC VISCOSITY (Kg/M*S): ";
270  INPUT VISC
300  (D(I-1) + D(I)) / 2
290  FOR I = 1 TO N
300  DM(I) = 1 TO N
310  NEXT I
320  C(0) = 0
```

```

330   FOR I = 1 TO N
340   C(I) = NP(I) * PDENS * 3.14159 / 6 * DM(I) ^ 3 * 1E - 9
350   C(0) = C(0) + C(I)
360   NEXT I
370   FOR I = 1 TO N
380   V(I) = 9.8 * (PDENS - WDENS) * DM(I) ^ 2 * 1E - 10 / (18 * VICS)
390   RE(I) = V(I) * DM(I) * WDENS * 1E - 8 / VISC
400   IF RE(I) < 1 THEN GOTO 420
410   V(I) = (0.7063 * (PDENS - WDENS) * (DM(I) * 1E - 6) ^ 1.6 * WDENS
      * ^ -0.4 * VISC ^ -0.6) ^ 0.714 * 100
420   NEXT I
430   FOR I = 1 TO N
440   T(I) = 10 / V(I)
450   NEXT I
460   PRINT "WHAT INTERVAL OF TIME DO YOU WANT? (sec): ";
470   INPUT DT
480   M = 1800 / DT
490   DIM CN(M), CF(M), TP(M)
500   TSUM = 0
510   CF(0) = 1
520   PRINT "C(t)/C(0)      TIME"
530   PRINT "                (sec)"
540   PRINT CF(0), TSUM
550   CN(0) = C(0)
560   FOR J = 1 TO M
570   TSUM = TSUM + DT

```

```
580   FOR I = 1 TO N
590   IF T(I) = 1E12 THEN GOTO 680
600   IF T(I) > TSUM THEN GOTO 670
610   CN(J) = CN(J - 1) - C(I)
620   CF(J) = CN(J) / C(0)
630   TP(J) = TSUM
640   PRINT CF(J), TP(J)
650   T(I) = 1E12
660   GOTO 680
670   CN(J) = CN(J - 1)
680   NEXT I
690   NEXT J
700   END
```

VITA

Patricia Mery was born in Santiago, Chile. She studied elementary and high school in that city, where she received her Licencia Secundaria in 1967. She studied mathematics at the Universidad de Chile in Arica, Chile, and civil engineering at the Pontificia Universidad Católica de Chile in Santiago, where she received her degree of Ingeniero Civil Con Mención En Hidráulica in December 1979.

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