1-1-1964

Electrostatic filtration of oils.

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ELECTROSTATIC FILTRATION OF OILS

BY

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A Thesis
Submitted to the Faculty of Graduate Studies Through the
Department of Chemical Engineering in Partial Fulfillment
of the Requirements for the Degree of
Master of Applied Science at
University of Windsor

Windsor, Ontario

1964

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ABSTRACT

When oil with particles suspended is passed through a foamed polymer placed in an electrostatic field, some of the particles will be adsorbed on the foam. This phenomenon is called electrostatic filtration. The purpose of this investigation is to find the correlation of variables, such as: t, residence time of suspension in filter; ψ, applied voltage; θ, concentration of stabilizing additives present in the suspension; β, concentration of particles in suspension after passing through filter; β_0, initial concentration of particles in suspension.

The experimental results showed the following empirical correlation:

$$\frac{\beta}{\beta_0} = \exp. \left[- K e^{-(C\theta)} \psi^2 (t + B\theta) \right] \qquad (4-6)$$

where K, C, and B are considered as constants.

ACKNOWLEDGEMENTS

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CHAPTER I

INTRODUCTION

Petroleum and chemical industries have a great deal of interest in phenomena which could be utilized for the removal of foreign or undesirable particulate matter from liquid process streams. For example, particles of rust and iron sulfide formed in storage and handling of crude oil distillate streams deposit on heat exchangers and on catalysts in subsequent oil processing. Accumulation of these deposits can result in considerable loss of money by causing poor equipment performance and eventually necessitating plant shut down. To solve this problem ordinary mechanical filters are sometimes installed in the process streams. This solution fails however in those cases where the particle sizes are small, with diameters of less than 10 microns. These particles pass through ordinary filters, whereas if fine pore size filters are used they become rapidly clogged.[1] In such instances it is impractical to use mechanical filtration and other more maintenance free filtration methods are desired.

It is possible that electrostatic filtration techniques which are being developed by several U.S. companies might provide a satisfactory solution to the type of problems described above. A study of the principles on which electrostatic filtration of solids from oils is based forms the subject matter of the work described here.

The ability of high electrical fields, both AC and DC, to

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1 Private correspondence to I. Koszman.

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separate dispersed phases had been known for a long time. Research Cottrell Incorporated, has developed commercial equipment capable of removing dust or mist from gas streams. Petreco has pioneered the development of equipment capable of removing water in oil emulsions. Essentially both of these processes depend on passing a given stream through a region of high electrical field in which phase separation takes place. Similar attempts to treat solid-in-oil suspensions had failed. It has been observed that solid particles in oil under influence of high electrical field undergo rapid and highly irregular movement without any significant change in concentration. Dielectrophoretic type of separation described by Pohl (3) is an exception rather than the rule. Recently, however, it was discovered that efficient solids-from-oil separation could be achieved if a porous, electrically insulating material such as polystyrene or polyurethane foam is placed between two electrodes and the suspension is passed through the foam. Solid particles become adsorbed and held on the foam as long as a high DC voltage is applied across it. When the voltage source is disconnected, most of the particles become released and could be washed off if the oil flow is continued. This discovery forms the basis of electrostatic filtration of solids from oils.

To the best of the author's knowledge, however, no study had been done concerning any correlations of the rate of filtration with the electrostatic field, flowrate, viscosity of the oil, and other variables.

The purpose of this investigation was, therefore, to correlate these important variables with the fraction of suspensoid removed by the elctrostatic filter. Furthermore, by knowing the general

empirical correlation, the optimum design of an electrostatic filter

for a particular application might be found.

CHAPTER II

THEORY

Although no comprehensive explanation of the phenomenon of electrostatic filtration had been published, one fundamental study of the application of highly non-homogeneous, strong electric fields to suspensions of solids or of liquids in poorly conducting fluids was done by Pohl (3) in 1950. Although the experimental system under this investigation lacks the simplicity of Pohl's model, it is suggested that the basic mechanism responsible for electrostatic filtration is similar in nature to that proposed by Pohl. A simplified version of the theory follows below (2) and (3).

Consider an electrically neutral spherical particle located in a nonhomogeneous electrical field, as shown in Figure 1. Under these conditions the particle will become polarized, i.e., a certain amount of positive charge q^+ will concentrate at one end of the particle and equal and opposite amount of charge q^- will concentrate at the other end. Assume that the distance between the centres of gravity of each charge, Δr, is small. It follows from elementary electrostatics that the net force on the particle will be given by

$$F = -q^-E(r) + q^+E(r + \Delta r) \qquad (2 - 1)$$

Expansion of $E(r+\Delta r)$ in Taylor's series about r, use of the assumption that $q^+ = q^- = q$ and substitution into equation (2 - 1) yields the result:

$$F = q\Delta r \frac{\partial E}{\partial r} \qquad (2 - 2)$$

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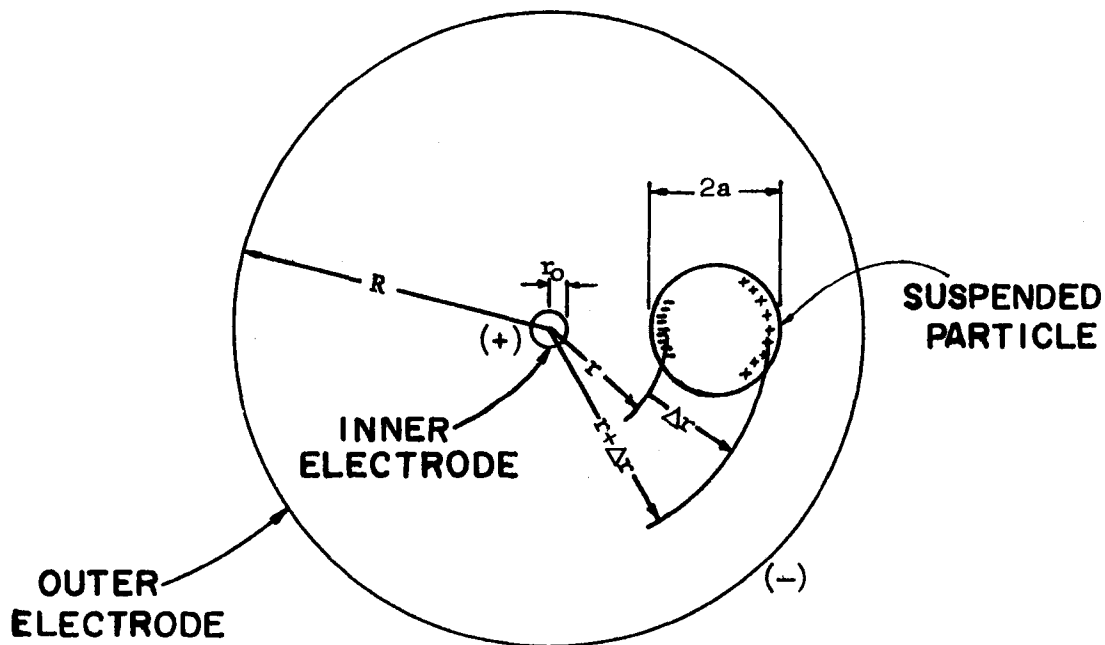
FIGURE 1. Forces operating on suspensoids in a non-
homogeneous electric field. The distance
between the centres of gravity of the in-
duced charges is represented by Δr.

The quantity $q\Delta r$ is known as the induced dipole moment and will be

denoted by p, so that

$$F = p\frac{\partial E}{\partial r} \qquad\qquad (\ 2 - 3 \ )$$

For a non-conducting particle of dielectric constant ϵ_1 in a medium of

dielectric constant ϵ_2, the dipole moment p is given by (1):

$$p = 4\pi \ \epsilon_2 \ \epsilon_0 \ [\ E \ \frac{\epsilon_2 - \epsilon_1}{\epsilon_1 + 2\epsilon_2} \ a^3 \ ] \qquad\qquad (\ 2 - 4a \ )$$

where ϵ_0 is the absolute dielectric constant of vacuum. If the particle

is a conductor,

$$p = - \ 4\pi \ \epsilon_2 \ \epsilon_0 \ a^3 \ E \qquad\qquad (\ 2 - 4b \ )$$

Let the potential of the centre electrode of Figure 1 with respect to the cylinder be ψ. Then the solution of Laplace's equation results in the formula for the field

$$E = \frac{\psi}{\ln R/r_o} \left(\frac{1}{r}\right) \qquad (2-5)$$

where r_o is the radius of the centre rod. Differentiation of equation (2 - 5) and subsequent substitution into (2 - 3) with the use of (2 - 4b) gives:

$$F = 4\pi \epsilon_2 \epsilon_0 \psi^2 a^3 \left[\frac{\epsilon_1 - \epsilon_2}{\epsilon_1 + 2\epsilon_2} \right] \frac{1}{r^3 (\ln R/r_o)^2} \qquad (2-6a)$$

Similarly for a conducting particle one obtains:

$$F = 4\pi \epsilon_2 \epsilon_0 \psi^2 a^3 \frac{1}{r^3 (\ln R/r_o)^2} \qquad (2-6b)$$

The nonuniformity of the elctrical field in the system under investigation is not only due to cylindrical geometry but is greatly amplified by the presence of the polyurethane foam. This becomes clear, if one realizes that the dielectric constant of the foam ϵ_3 differs from that of the oil, ϵ_2. Although the real system deviates significantly from that described by equations (2 - 6a) and (2 - 6b), it is reasonable to assume that the essential features of the equations remain the same. Thus it would be expected that the force on the particle should be of the form:

$$F = \epsilon_2 \epsilon_0 \psi^2 a^3 f \qquad (2-7)$$

where f is a function of ϵ_1, ϵ_2, ϵ_3 and various geometrical parameters. This force on the particle must be counterbalanced by viscous drag which may be assumed to be given by Stoke's equation

$$F = 6\pi \mu a u \qquad (2-8)$$

where μ is the viscosity of the oil and u is the velocity of the particle.

Combination of equations (2 - 7) and (2 - 8) yields the result

$$u = \frac{\epsilon_2 \epsilon_o \psi^2 a^2}{\mu} g \qquad (2-9)$$

where $g = f/6\pi$. Next it is assumed that the particles diffuse and are adsorbed on the foam at the rate proportional to their velocity and concentration. The above statement is equivalent to

$$\frac{dn}{dt} = - k_1 u n \qquad (2-10)$$

where n is particle concentration and k_1 is a proportionality constant.

Integration of (2 - 10) and substitution of (2 - 9) yields

$$\frac{n}{n_o} = \exp. \left[- k' \frac{\epsilon_2 \epsilon_o (\psi/R)^2 a^2}{\mu R^2} t \right] \qquad (2-11)$$

where $k' = k_1 g R^4$. This substitution is made for two reasons. It is expected that the rate of particle removal should be dependent on the voltage gradient across the foam, and not on the voltage difference between electrodes alone. Furthermore this substitution leaves the unknown constant k' dimensionless.

The experimental work described in a later section of this thesis provides partial verification of the proposed mechanism of particle removal by electrostatic filtration.

CHAPTER III

EXPERIMENTAL ARRANGEMENT AND PROCEDURE

A. <u>APPARATUS</u>

1. Main Set Up

The main set up of the apparatus used for this investigation might be divided into three parts as follows:

(a) Electrostatic Filter

For the purpose of measuring the efficiency of filtration, the filter constructed like a flow reactor was believed to have the most advantages. Since the precipitation of suspensoids, which was of interest in this study, occurs during the residence period in an electrostatic field only, a cylindrical filter was employed as shown in Figure 2.

It consisted of two removable circular shaped pieces of plexiglass fixed at the two ends of a copper cylinder with an I.D. of 5.192 cm and length of 22.7 cm. An inlet and an outlet were made on the plexiglass cover plates at each end. A brass rod 0.314 cm in diameter was placed at the centre of the cylinder with one end held by the plexiglass inlet plate and the other end fitted through the other plate to be attached to a high voltage supply. Two "0"-rings were used to prevent the leakage between the plexiglass plates and the cylinder. A very small "0"-ring was used between the centre rod and the outlet plexglass plate for the same purpose.

A polyurethane foam 19.05 cm in length with a centre hole

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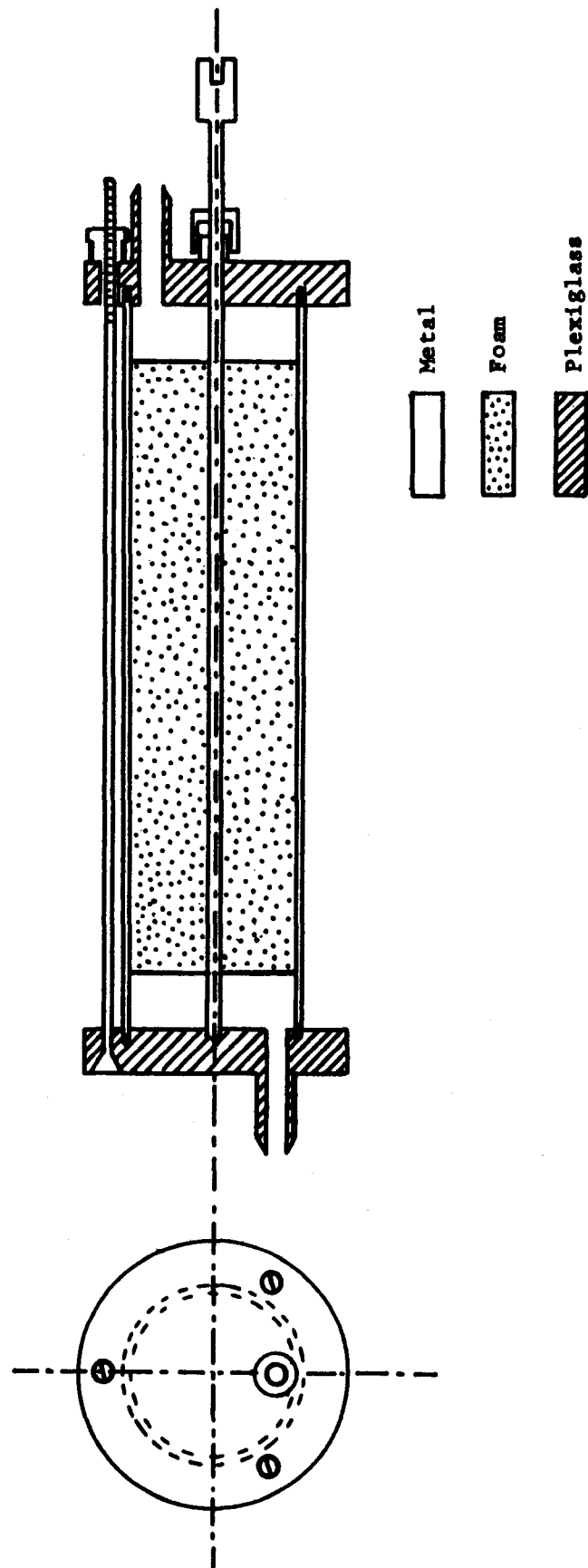
FIGURE 2   CROSS-SECTION OF FILTER

Metal

Foam

Plexiglass

just large enough for the brass rod to go through was placed in the cylinder. The diameter of the foam was cut by means of a hot wire exactly to the inside diameter of the cylinder, so that there was neither space between them nor excess pressure on the foam.

The reason for the above construction design was determined by the application of a high voltage difference between the centre rod and the cylinder, which produced a cylindrically symmetric and a longitudinally uniform electrostatic field.

Although the filtration is independent of gravitational force in this investigation, the cylinder was placed at about 45° from the horizontal level with the outlet above the inlet to insure removal of any air trapped in the cylinder for the each run.

This investigation was carried out at a temperature of 25°C. The room temperature was also partially controlled so that the temperature of oil at the outlet was negligibly different from 25°C. during the each run.

(b) Oil Flow and Recirculation

Figure 3 is a diagram showing the overall system which was designed for this investigation. Tank A with a volume of about 100 litres used for storing the prepared suspension, was placed about 5 feet above the filter and connected with copper and tygon tubing from the bottom to the inlet of the filter to cause the flow of suspension by gravitational force. An air trap and flow controlling needle-valve were attached to the connecting tubing. The outlet of the filter was connected with tygon tubing to a volumetric flowmeter. The effluent from the flowmeter was discharged to tank B.

Synthetic suspensions were prepared by mixing measured
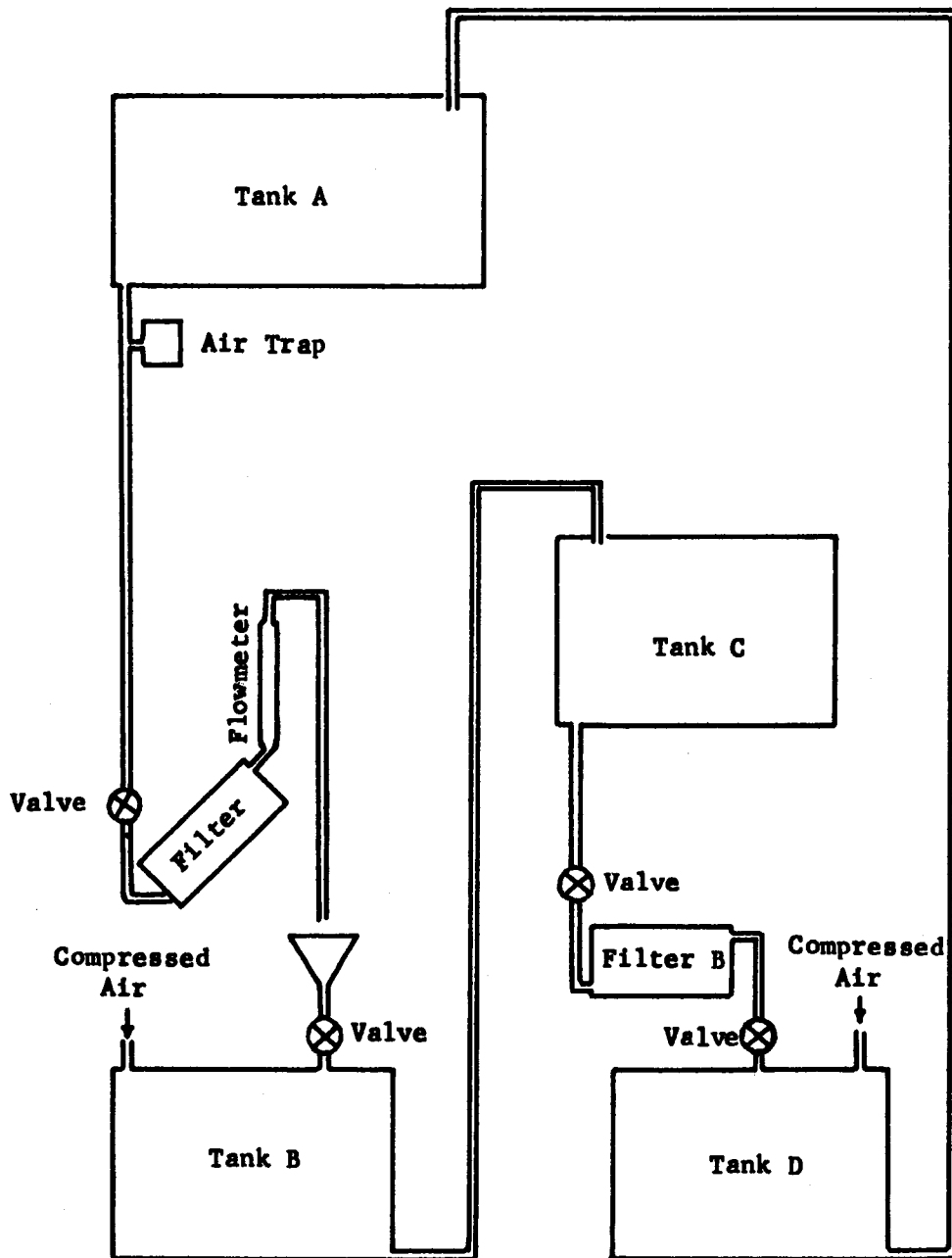
FIGURE 3   SCHEMATIC DIAGRAM

amounts of commercially available stabilized concentrated graphite sus-
pension (primarily Dixon No. 10) into the oil in tank A. The concen-
trated suspensions contain stabilizing additives. It had been discovered
during several initial runs that the performance of the electrostatic
filter depended strongly on the concentration of the additive in the
oil used.

In order to have the same additive concentration while vary-
ing the initial concentration of the graphite particles in the oil the
following recirculation system was designed:

A sealed tank B with an on-and-off valve at the inlet and a
compressed air inlet at the top was connected with a copper tube
leading from the bottom of tank B to the top of tank C. Tank C was
placed about 5 feet above tank B. From the bottom of tank C a copper
tube with a needle-valve and another electrostatic filter was connected
to the top of tank D which was placed at the same level as tank B.
Tank D was of similar construction to tank B except that the outlet
was let to tank A instead of tank C.

The flow of oil from tank B to tank C or from tank D to tank
A was caused by passing compressed air into tank B or tank D respec-
tively. The flow of oil from tank A to tank B or from tank C to tank
D was caused by gravitational force.

(c) Electrical Circuits

In order to establish an electrostatic field in the filter,
a high voltage DC supply was adopted for applying a DC voltage
difference between the centre rod and cylinder of the filter. This
device provided a voltage controllable in the range from 0 to 35 kilo-
volts with a voltage and milliamperage scale showing direct readings

of the output conditions. For a stable DC voltage output an electrical regulator was employed to supply the high voltage device with a constant AC power input.

The temperature of prepared suspension in tank A was maintained at $25.0^{\circ}C$. during each run by a sensitive temperature regulator. An adjustable speed stirrer was also employed in order to keep the temperature and the concentration of the suspensoid uniform in tank A.

2. Measuring Apparatus

Besides the high voltage DC supply and the flowmeter from which direct readings could be taken, there were two other variables on which measurements were made as follows:

(a) Viscosity Measurement

A synchro-lectric viscometer, manufactured by the Brookfield Engineering Laboratories, was adopted for measurements of viscosities of oils used in the experiments. The LVT model gave a dial reading from which the viscosity in poises was easily obtained. Each measurement was made in a constant temperature bath at $25.0^{\circ}C$. This viscometer was guaranteed to be accurate to within 1 percent of full scale value and to have reproducibility of 0.2 percent.

(b) Concentration of Particles

Direct counting methods for determining particle concentrations in oils are very tedious. Since a large number of samples had to be analyzed, a simple and rapid procedure was needed. It was found that light transmission through a sample of suspension using the "Spectronic 20" colorimeter obeyed Beer's Law as shown on Figure 2. This plot was obtained by arbitrarily assigning a value of particle concentration of 100 at 2 percent light transmission. Other data

points on the plot were obtained by dilution of the standard (100 con-
centration units) oil with measured amounts of particle free oil.
Assuming that during electrostatic filtration particle size distribution
in the oil does not change significantly, one could determine the
particle concentration in arbitrary units (called β) by measuring light
transmission in the filter effluent sample and using the calibration
curve of Figure 4. Thus the procedure used yielded a number which
should be proportional through an unknown factor to particle concentra-
tion. In a later section it will be shown that only the ratio of the
particle concentration in the filter effluent to that entering the
filter is a significant quantity. Thus the unknown proportionality
factor cancels out. This fact, coupled with experimental reproduci-
bility and correlations developed provides some justification for the
procedure used.

It was found that the filter effluent usually contained
sufficient electrostatic charge to cause nonuniform distribution of
particles in the sample collected. This difficulty was resolved by
collecting a 500 ml. sample in a beaker, and waiting for about 15
minutes for complete charge dissipation before the sample was analyzed.

The samples were compared in the colorimeter using 6" x 3/4"
matched test-tubes.

B. EXPERIMENTAL PROCEDURE

1. Preparation of Initial Suspension

Concentrated colloidal graphite in petroleum oil containing
10 percent solids with stablizing additives and made by the Joseph
Dixon Crucible Company was used. The manufacturer stated that 75
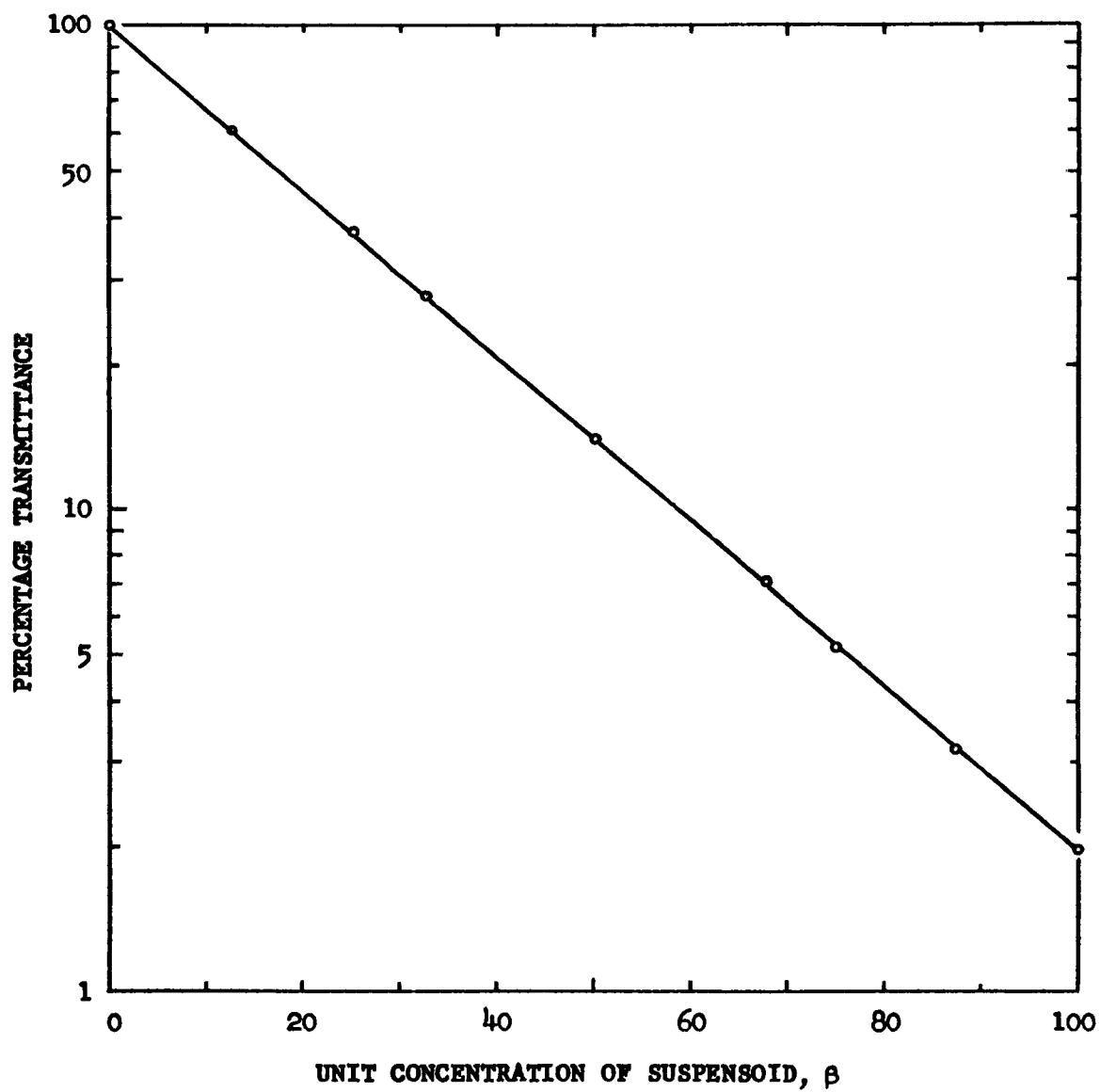
FIGURE 4   CALIBRATION CURVE OF LIGHT TRANSMISSION

percent of the particles range from 3 to 5 microns in diameter, the remaining 25 percent being smaller. It was observed that no particles settled during the experiments which took about 5 months. Therefore, it was reasonable to assume that each gram of the concentrated colloidal suspension taken contained the same graphite particle and additive concentration.

Suspensions were prepared by mixing a desired amount of the concentrated colloidal suspension with up to 20 gallons of particle free petroleum solvent (primarily "Varsol") depending on the requirements for the initial condition of the suspension. The concentration of additive was reported as grams mass of the concentrated colloidal suspension added, divided by the total volume in litre of the solvent.

The prepared suspension was stored and stirred in tank A at 25.0°C. for at least 2 hours before use.

2. Filtration

The phenomenon of electrostatic filtration described in this work depends on the presence of a non-conducting matrix, such as polyurethane foam in a high electrical field. This was checked by noting that no change in particle concentration occured in absence of the foam at all voltages and flow rates used. Furthermore no change was noted in the presence of the foam if no electrical field was applied.

A typical experiment was run by flowing the prepared suspension through the filter containing a specified polyurethane foam at constant applied voltage. Effluent particle concentration data were taken at various flowrates ranging from 90 ml/min to 1100 ml/min at steady state conditions. It was found that a total flow of oil

approximately three times the filter volume was sufficient to achieve steady state at each flowrate. The reproducibility of the data was checked by repeating the first measurement at the end of each run. Reproducibility of 3 to 5 percent was considered satisfactory and was actually obtained in most of the runs.

Particles which accumulated on the foam during a given run were washed out by passing some fresh filter feed through the foam in the absence of applied voltage. This was done at the beginning of each run.

3. Recirculation

In many cases a change in particle concentration was desired at constant additive concentration. The recirculation system was designed for this purpose. By applying a strong electrostatic field on filter B with slow flowrate from tanks C to D, clean oil with a known additive concentration was obtained and stored in tank D for use in preparing a new suspension with any combination of concentration of particles and additives.

For example, addition of oil purifed in filter B to a portion of unused suspension in tank A would result in a suspension of a reduced particle concentration with the same additive concentration. On the other hand further addition of concentrated colloidal suspension would result in an oil suspension of higher additive and particle concentration. Additive and particle concentration could be reduced by additions of fresh oil. Oils, in which additive concentration built up to a very high value were discarded.

It was insured that the transmittance of the oil in tank D was always above 97 percent in comperison with the practically

particle-free oil as 100 percent. The practically particle-free oil

was obtained by passing the oil from tank D through a millipore filter

paper with the specified maximum pore sizes of 0.45 micron in diameter.

CHAPTER IV

EXPERIMENTAL RESULTS AND DATA ANALYSIS

A. GENERAL

As was mentioned previously since no comprehensive work had
been published, the experiments done in this investigation were based
on trial-and-error analysis of data, which led to a final empirical
expression as follows:

$$\frac{\beta}{\beta_o} = \exp. \ [\ - \ K \ e^{-(C\theta)} \psi^2 \ (t + B\theta) \ ] \qquad (\ 4 - 1 \ )$$

where β_o : concentration of particles, β, at the initial condition,

ψ : voltage difference acorss the electrostatic field,

t : residence time for suspension in the filter,

θ : additive concentration,

K, C, B : constants.

All the numerical data for curves shown in this chapter have
been listed in Appendix III.

B. THE PARTICLE CONCENTRATION AT OUTLET OF FILTER

WITH RESPECT TO RESIDENCE TIME

Figure 5 was drawn to show the measurements of the particle
concentration at the outlet of the filter with respect to residence
time t, which was calculated from determinations of foam porosity,
bulk foam size, and flow velocity. A plot of the same data on semilog
graphpaper as in Figure 6 showed "almost the same behaviour as first
order chemical reaction." From the curve the following empirical

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CURVE	VOLTAGE APPLIED	POLYURETHANE FOAM	ADDITIVE CONCENTRATION
(A)	15 kv	10 ppi	1.092 gm/l
(B)	10 kv	60 ppi	0.747 gm/l
(C)	10 kv	45 ppi	0.863 gm/l

μ = 0.917 cps
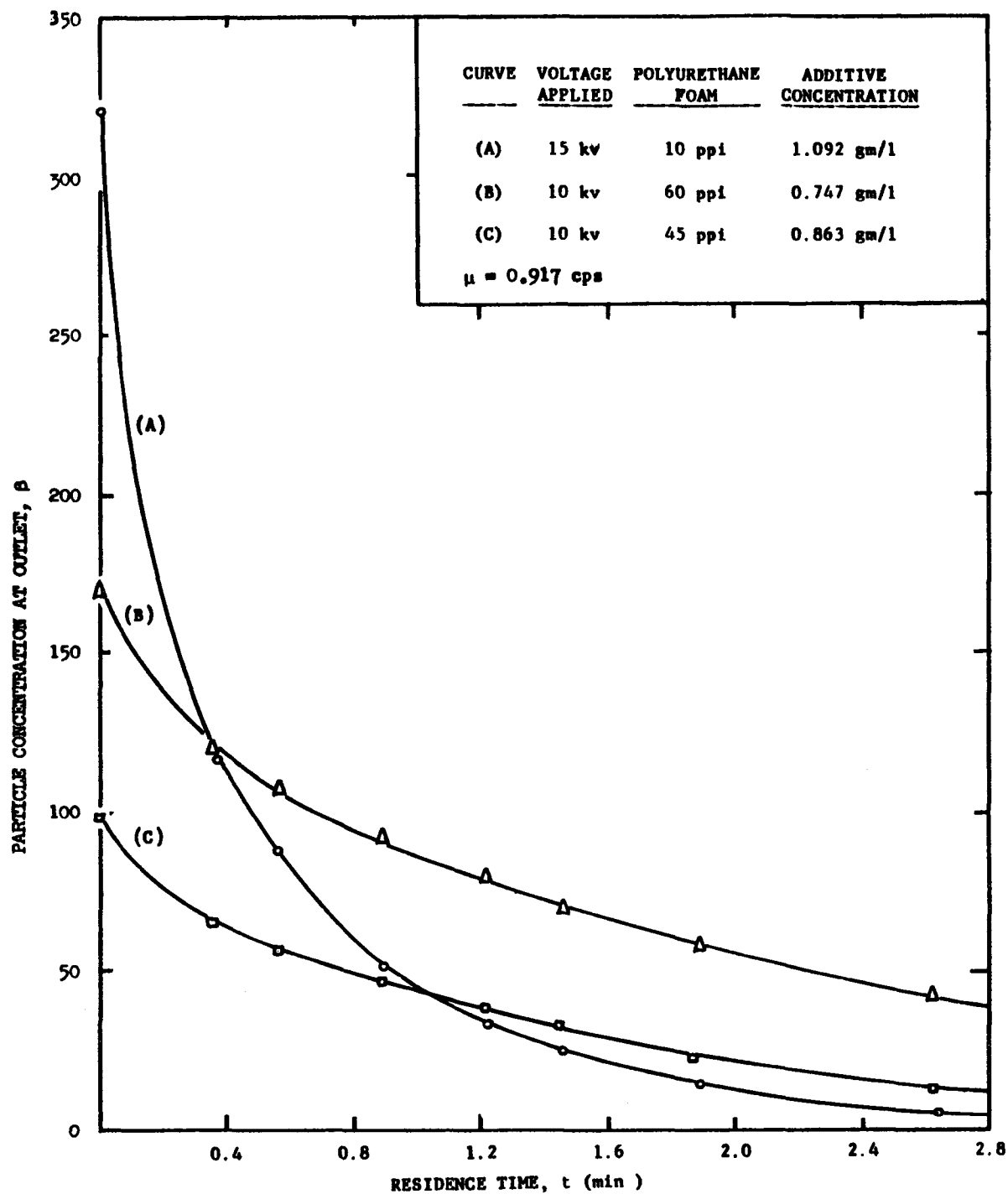
FIGURE 5   PARTICLE CONCENTRATION AT OUTLET OF FILTER (I)
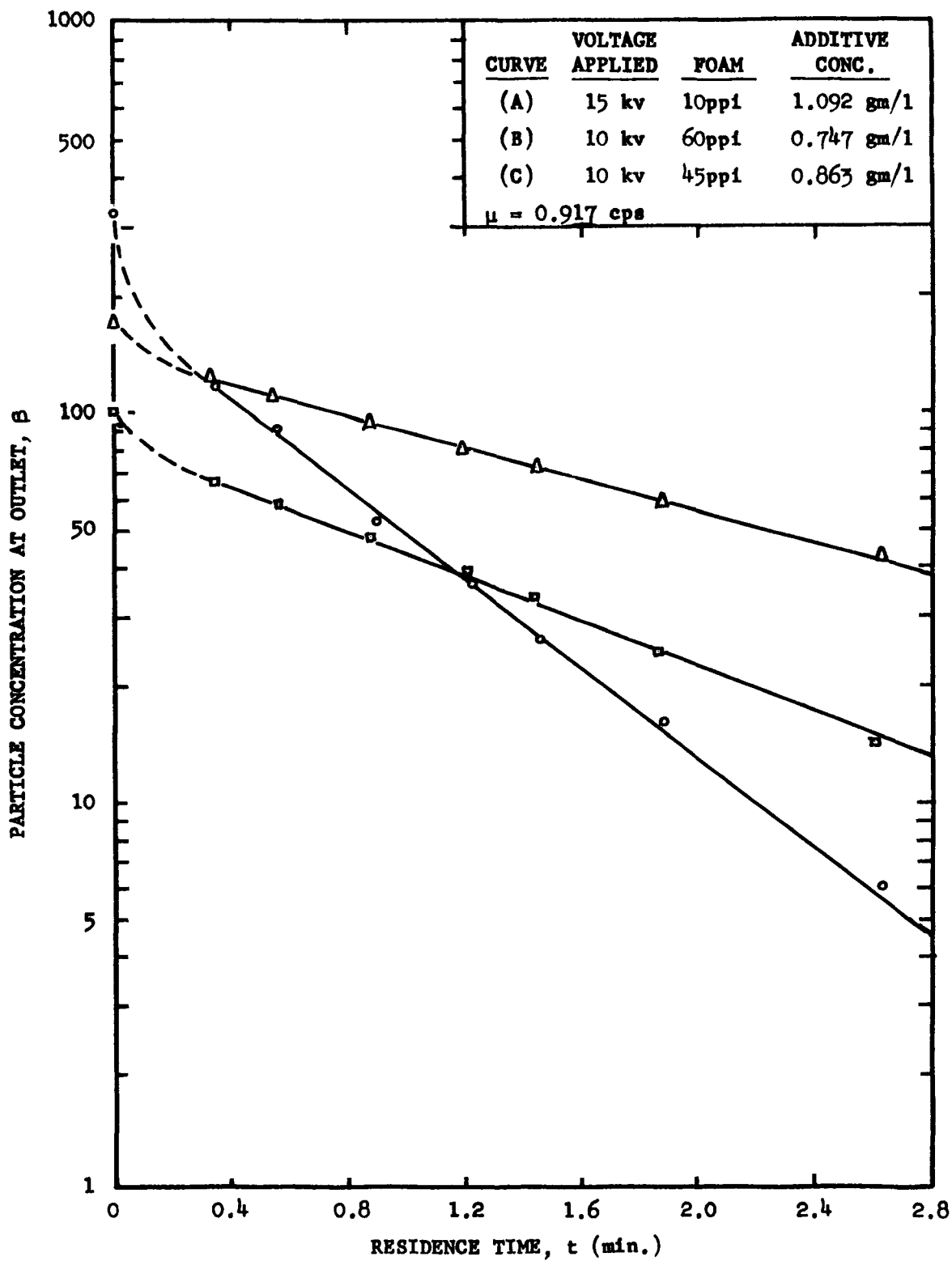
FIGURE 6   PARTICLE CONCENTRATION AT OUTLET OF FILTER (II)

CURVE	VOLTAGE APPLIED	FOAM	ADDITIVE CONC.
(A)	15 kv	10ppi	1.092 gm/l
(B)	10 kv	60ppi	0.747 gm/l
(C)	10 kv	45ppi	0.863 gm/l

μ = 0.917 cps

expression was arrived at:

$$\beta = \beta_0 \exp. \left[- k_1 \left(t + C' \right) \right] \qquad (4 - 2)$$

where k_1 is a constant which is the slope of each curve and C' is a correction term for the deviation. This relationship applies only to those values of contact time for which measurements were possible. It obviously does not hold for contact times approaching zero.

C. INITIAL CONCENTRATION DEPENDENCE

In order to determine the effect of initial particle concentration on the degree of retention which is defined as the fraction of the original particles remaining in the oil (β/β_0), two sets of runs were made in which all variables were held constant except the initial particle concentration and flowrate.

Figures 7 and 8 show the results of these experiments. This result confirms equation (4 - 2) formulated above, and provides justification for the method of particle concentration measurement used.

These experiments lead to the important conclusion--"the degree of retention is independent of the initial concentration of particles."

D. VOLTAGE DEPENDENCE

From the empirical expression (4 - 2) it was suspected that the slope, k_1, depended on the voltage difference applied to form the electrostatic field. In order to correlate k_1 and voltage, two sets of experiments were done with different voltages but with the same additive concentration for each set. The result for one set of runs is shown on Figure 9 from which the slopes of the lines were determined.
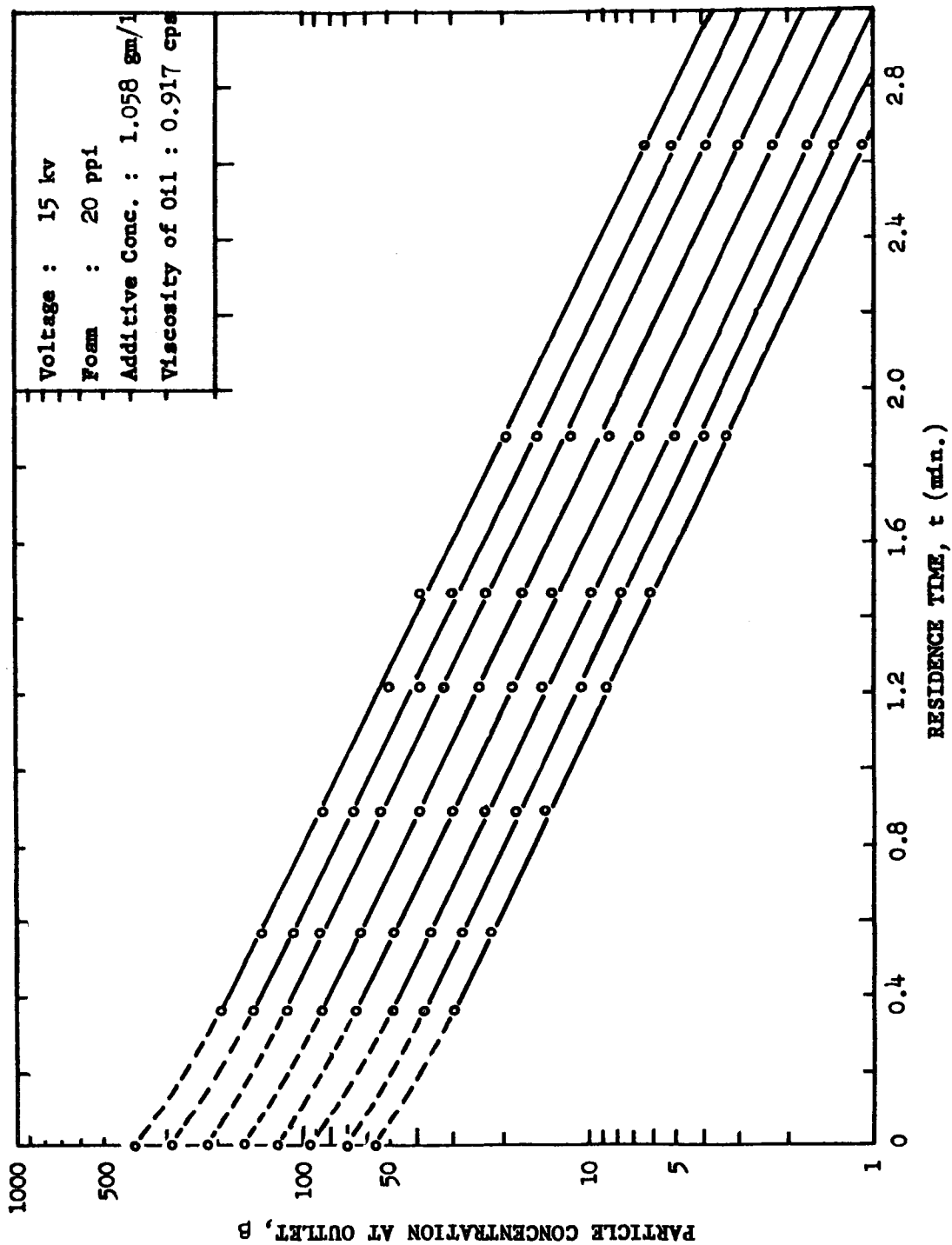
FIGURE 7 PARTICLE CONCENTRATION AT OUTLET OF FILTER FOR DIFFERENT INITIAL CONCENTRATION

Plot parameters:
Voltage : 15 kv
Foam : 20 ppi
Additive Conc. : 1.058 gm/l
Viscosity of Oil : 0.917 cps

X-axis: RESIDENCE TIME, t (min.)
Y-axis: PARTICLE CONCENTRATION AT OUTLET, β
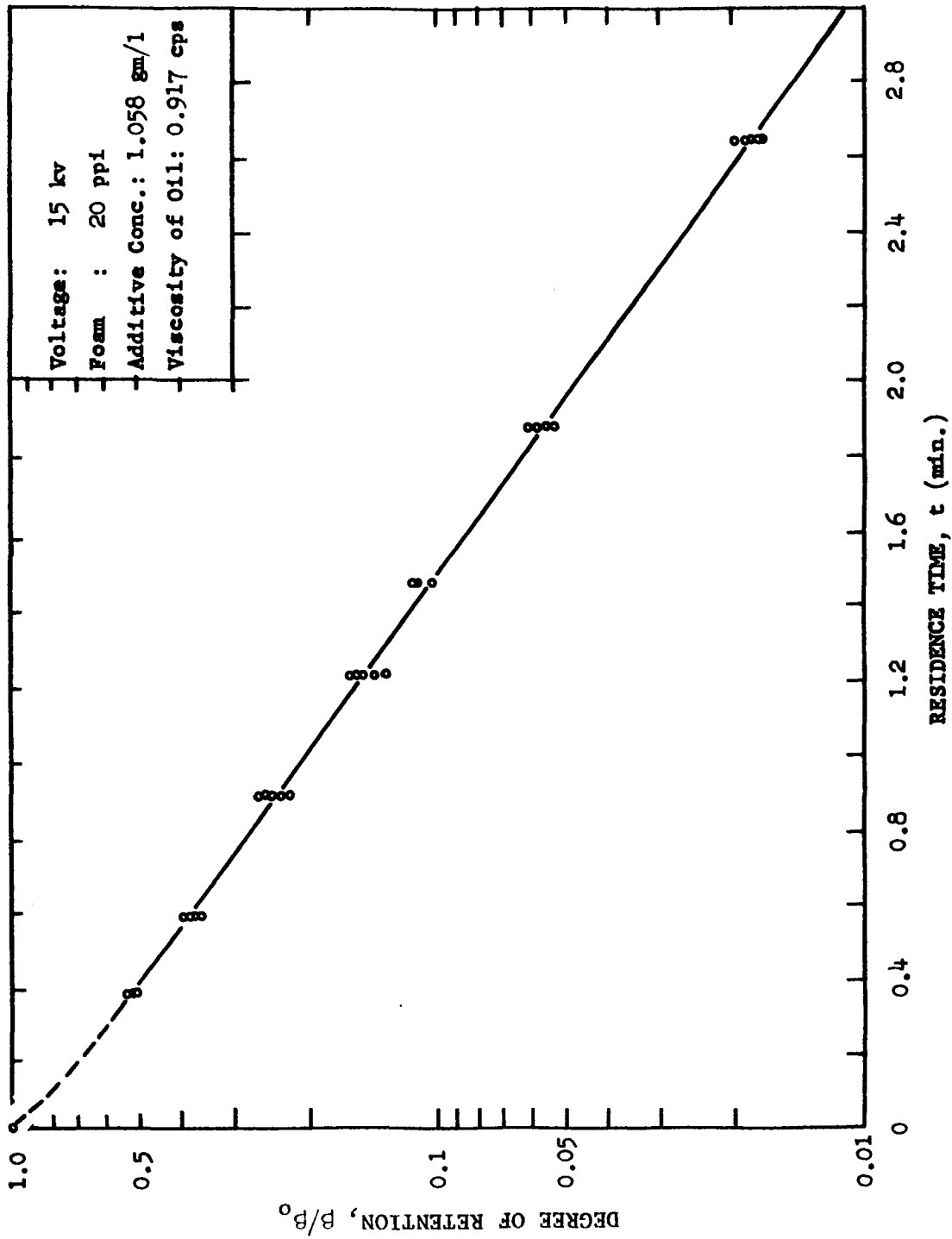
FIGURE 8   DEGREE OF RETENTION--INITIAL CONCENTRATION DEPENDENCE
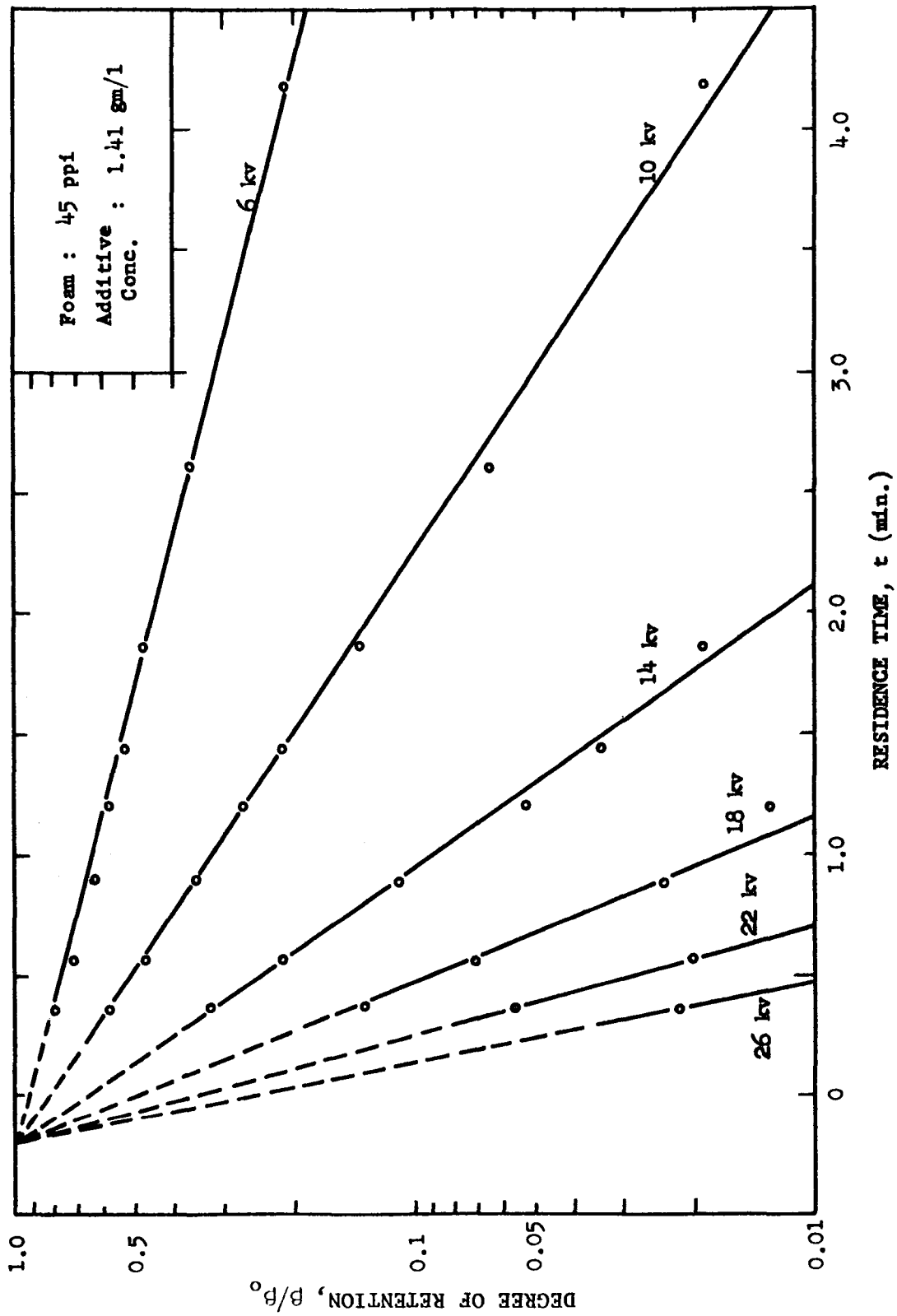
FIGURE 9   DEGREE OF RETENTION--VOLTAGE DEPENDENCE

These and the slopes obtained from the other set of runs were plotted on Figure 10. The slope of the line drawn on Figure 10 has a value of 2.0.

It is concluded from these plots that "the filtration rate constant k_1 is proportional to the square of the applied voltage and that the correction term C' is independent of voltage."

This statement when incorporated into the empirical equation results

$$\frac{\beta}{\beta_0} = \exp. \left[- k_2 \psi^2 (t + C') \right] \qquad (4 - 3)$$

where $k_2 = k_1/\psi^2$.

E. ADDITIVE CONCENTRATION DEPENDENCE

Because of the policy of the colloids manufacturer, the composition of the stabilizing additive was not available. However, the definition of additive concentration, θ, as gram mass concentrated colloidal graphite divided by volume of solvent in litre, certainly yields a number which is proportional to additive concentration and will differ from the real concentration by a constant factor only. Therefore, the nature of the correlation between k_2 and θ should be the same as if actual concentration had been used.

A series of runs were made to determine the nature of the additive concentration dependence. The results were shown on Figure 11 from which by trial-and-error analysis a plot of log k_2 against θ yielded a straight line as shown on Figure 12. This curve obeys the following empirical expression:

$$k_2 = K e^{-(C\theta)} \qquad (4 - 4)$$

CURVE	FOAM	ADDITIVE CONCENTRATION
(A)	45ppi	1.41 gm/1
(B)	45ppi	1.71 gm/1
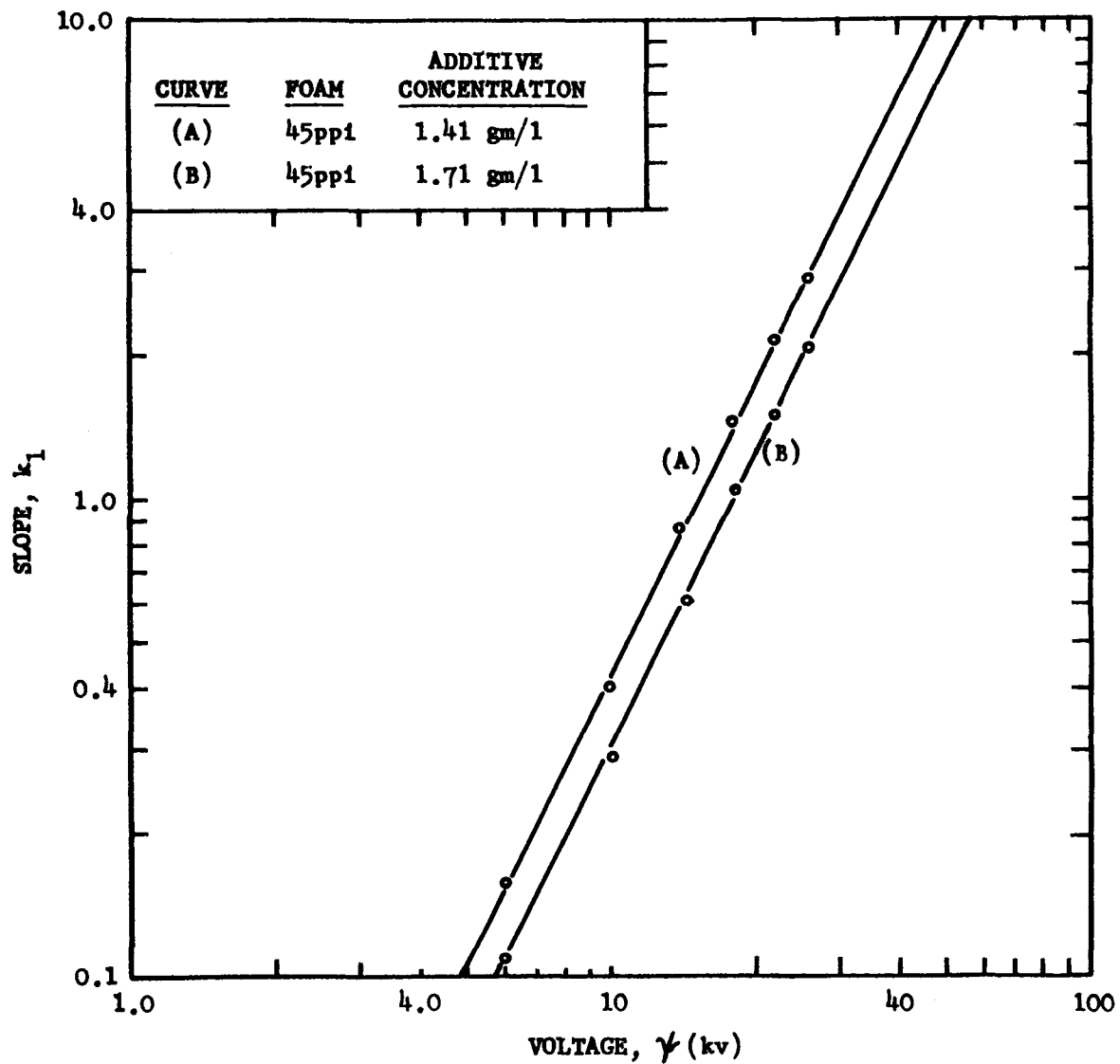
FIGURE 10   BEHAVIOUR OF VOLTAGE DEPENDENCE
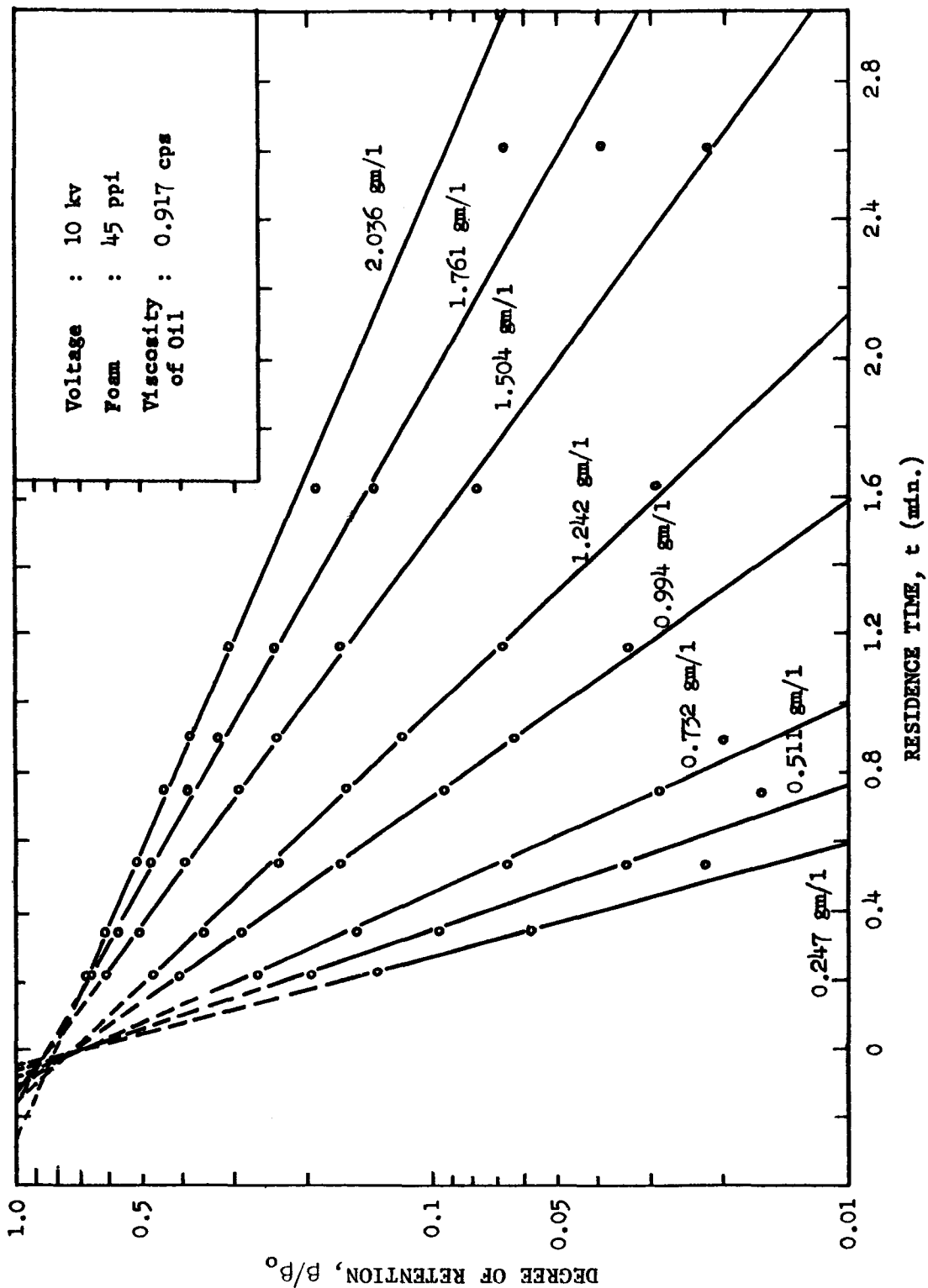
FIGURE 11   DEGREE OF RETENTION--ADDITIVE CONCENTRATION DEPENDENCE

Voltage : 10 kv
Foam : 45 ppi
Viscosity of Oil : 0.917 cps

ADDITIVE CONCENTRATION, θ (gm/1)

SLOPE, k_2
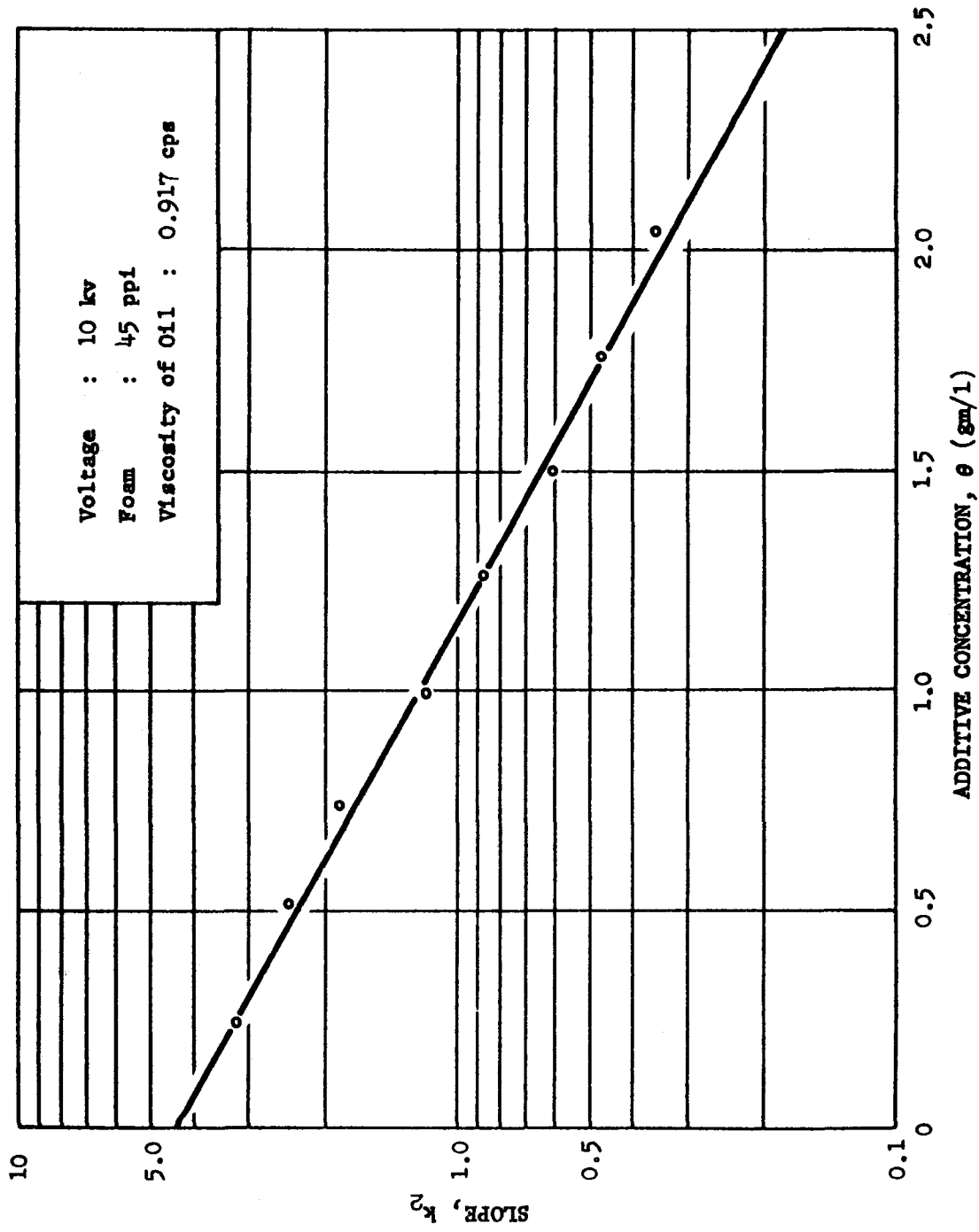
FIGURE 12   BEHAVIOUR OF ADDITIVE CONCENTRATION

where K and C are constants.

Figure 11 also illustrates that the correction term C' is a function of the additive concentration. A linear plot of C' against θ was shown on Figure 13. Despite the large scatter it appears that in the limit of zero additive concentration the correction term vanishes. The dependence of C' on additive may be approximated by:

$$ C' = B\theta \qquad\qquad (4 - 5) $$

where B is a constant.

It should be noted, however, that the additive concentration dependence shown may be different for other additives. Furthermore, it only holds valid for a limited range of concentrations. Data taken at large additive concentrations did not yield any regular behaviour.

The additive dependence described when incorporated into the empirical equation results in:

$$ \frac{\beta}{\beta_o} = \exp. \left[- K\, e^{-(C\theta)}\, \psi^2\, (t + B\theta) \right] \qquad (4 - 6) $$

In conclusion it may be stated that "the dependence of degree of retention on stabilizing additive is strong and may be quite complex."

F. PORE SIZE DEPENDENCE

Six different pore sizes of polyurethane foam were used for this experiment. These foams were 10, 20, 30, 45, 60, and 80 pores per linear inch (ppi.), which had true surface areas of 4.76, 10.50, 16.73, 26.90, 37.73, and 52.82 cm^2 per cm^3 respectively.

From the results of this experiment it was noted that these different pore sizes of foam formed complex correlations. In order to
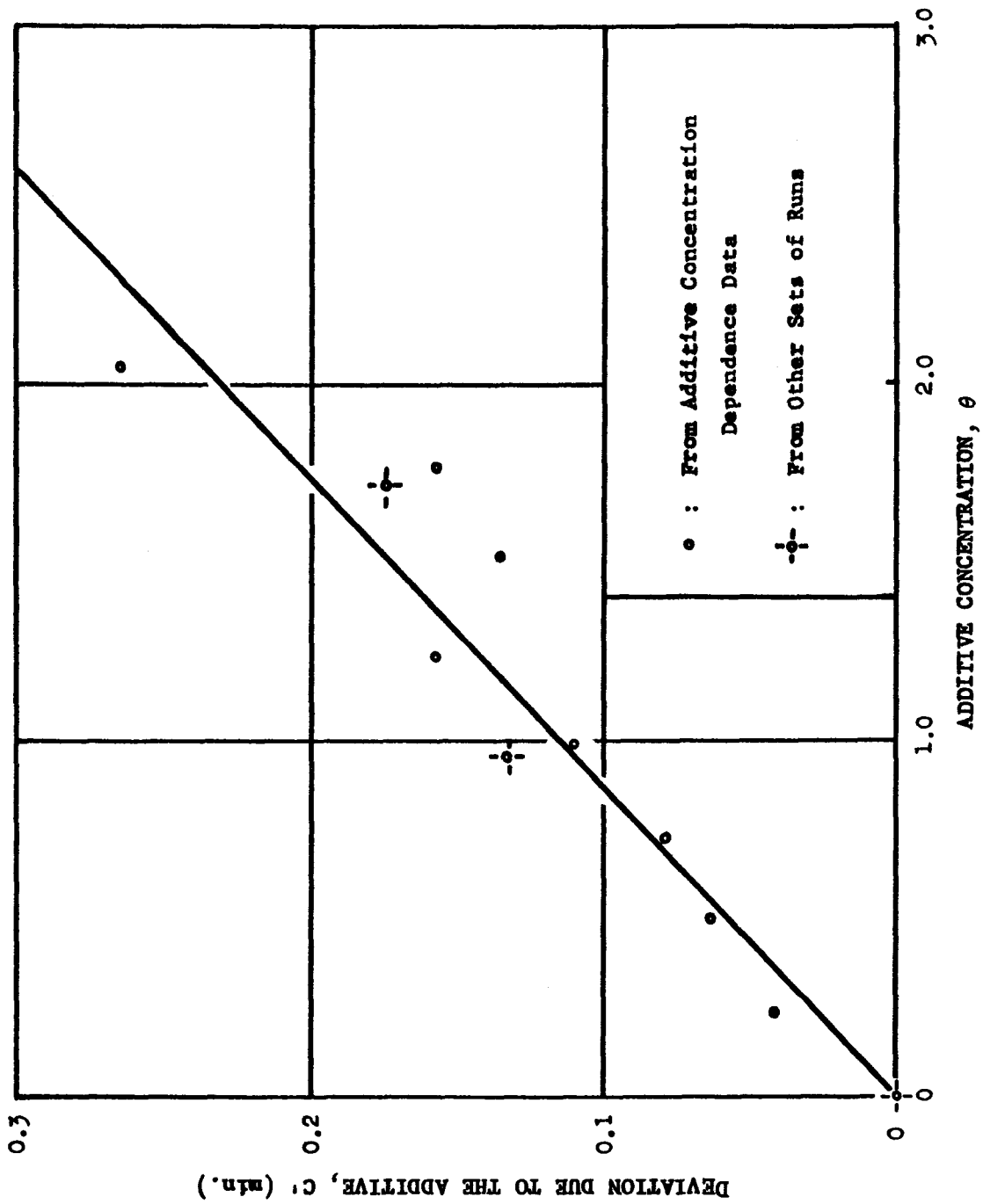
FIGURE 13   CORRECTION TERM AS A FUNCTION OF ADDITIVE CONCENTRATION

determine the correlations, it is believed that the effect of geometrical factor, such as surface roughness, pore distribution, pore shape, etc. of foam on the electrostatic field, will have to be studied.

CHAPTER V

DISCUSSION OF RESULTS

The results of the experimental measurements for non-vanishing

contact times are summarized by equation (4 - 6)

$$\frac{\beta}{\beta_0} = \exp. \; [\; - \; K \; e^{- (C\theta)} \psi^2 \; (t + B\theta) \;] \qquad (\; 4 \; - \; 6 \;)$$

The theoretical development based on zero stabilizing additive

concentration gave the result

$$\frac{n}{n_0} = \exp. \; [\; - \; k' \; \frac{\epsilon_2 \; \epsilon_0 \; (\psi/R)^2 \; a^2}{\mu \; R^2} \; t \;] \qquad (\; 2 \; - \; 11 \;)$$

It was shown that the ratio of the concentration in arbitrary

units should equal the corresponding concentration ratio in correct

units, i.e.

$$\frac{\beta}{\beta_0} = \frac{n}{n_0} \qquad (\; 5 \; - \; 1 \;)$$

Furthermore, for zero additive concentration, where the theoretical

and empirical results should be compared, the empirical equation

reduces to:

$$\frac{\beta}{\beta_0} = \exp. \; [\; - \; K \psi^2 \; t \;] \qquad (\; 5 \; - \; 2 \;)$$

Comparison of equations (5 - 2) with (2 - 11) shows that the voltage

and contact time dependences have been verified experimentally, and

that the empirical constant K should be given by:

$$K = k' \frac{\epsilon_2 \; \epsilon_0 \; a^2}{\mu \; R^4} \qquad (\; 5 \; - \; 3 \;)$$

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Assuming that equation (5 - 3) is valid, it then follows that a more general correlation in the presence of the additive should be of the form

$$\frac{\beta}{\beta_0} = \exp. \left[- k'' \frac{\epsilon_2 \epsilon_0 a^2}{\mu R^2} (\psi/R)^2 e^{-(C\theta)} (t+B\theta) \right] \qquad (5 - 4)$$

where k'' is dimensionless, B has a unit of min-1/gm, and C must have a unit of reciprocal concentration. For 45 ppi. foam C = 1.280 1/gm and B = 0.116 min-1/gm. Since the exact particle radii are not known, the quantity a^2/R^2 may be absorbed by the dimensionless constant k'' yielding a new dimensionless constant m. It should then be possible to correlate all of the data for each foam size by plotting two dimensionless groups, i.e.,

$$\left[\log \frac{\beta}{\beta_0} \right] \text{ againt } \left[\frac{\epsilon_2 \epsilon_0}{\mu} (\psi/R)^2 e^{-(C\theta)} (t+B\theta) \right].$$

This correlation based on 45 ppi. foam was shown on Figure 14, from which it was also possible to judge the accuracy of the data.

In conclusion, it may be stated that a new dimensionless group has been found which is related to the ratio of dielectro phoretic to viscous forces acting on a particle, and that its use allows one to correlate the performance of electrostatic filters under a variety of condition.
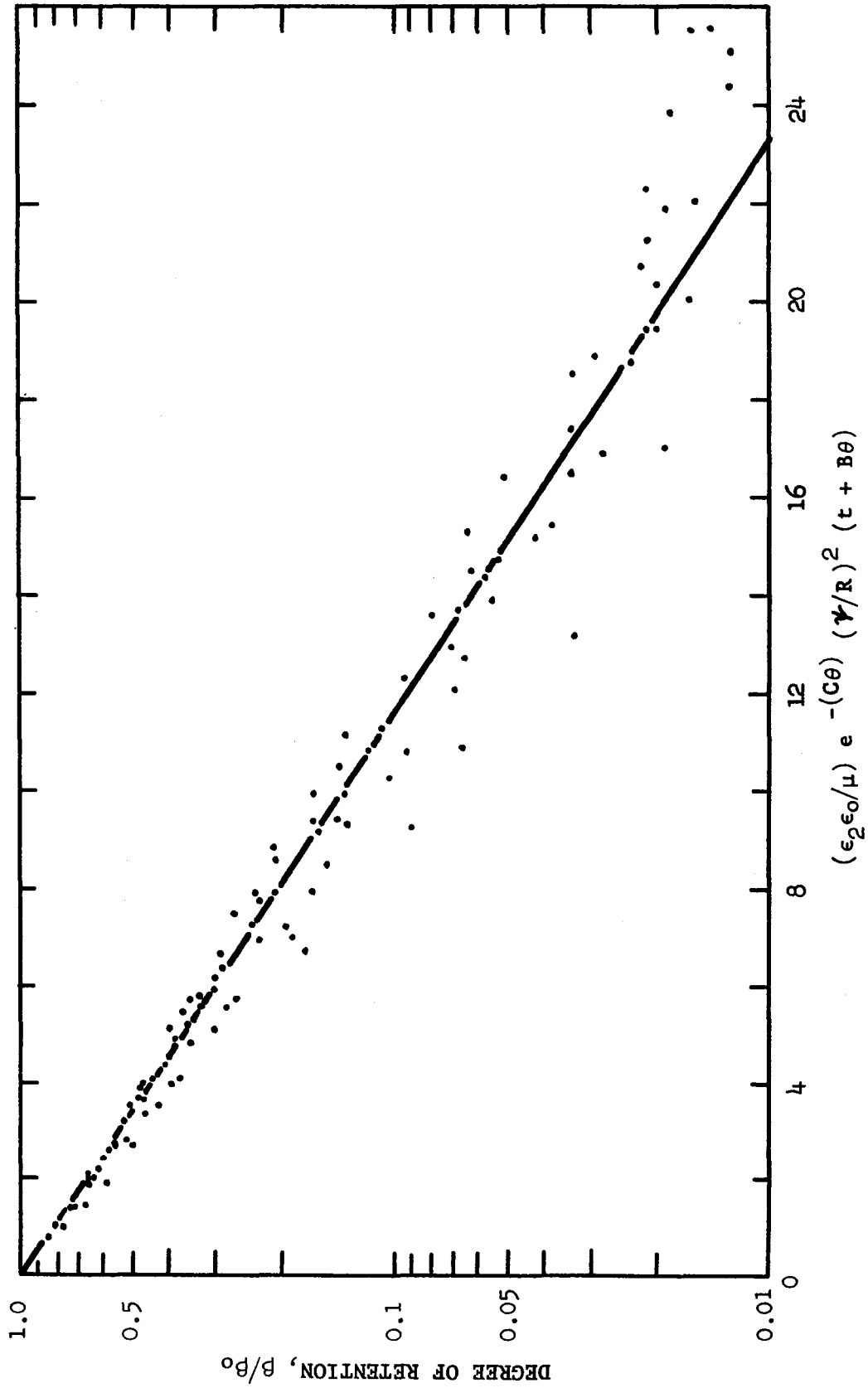
FIGURE 14   DIMENSIONLESS PLOT OF 45ppi FOAM DATA

$$(\epsilon_2 \epsilon_0/\mu) \ e^{-(C\theta)} \ (\mathcal{V}/R)^2 \ (t + B\theta)$$

DEGREE OF RETENTION, β/β_0

CHAPTER VI

FUTURE RESEARCH

This investigation has yielded a correlation amongst some important variables in the phenomenon of electrostatic filtration. It is recommended that this study be pursued further and the validity of the dependence on other parameters as predicted by the theory be verified.

In particular the dependence on dielectric constant, particle size, composition, and distribution, temperature, oil viscosity, filter diameter, length and geometry, and several known stabilizing additives should be investigated experimentally.

In addition other studies of the pertinent phenomena should be made:

(1)   Transient behaviour of the electrostatic filter,

(2)   The effect of AC or other forms of electrical fields,

(3)   Studies of the dependence on electrical conductivity of the oil.

(4)   Measurement of amounts of suspensoids that can be retained on different types of foam,

(5)   Studies of the means by which adsorbed particles can be removed from the foams.

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NOMENCLATURE

a = radius of suspensoid, micron,

A = surface area of foam, cm^2,

B = constant in equation $(4 - 1)$, min-1/gm,

C = constant in equation $(4 - 1)$, $1/gm$,

E = electrostatic field strength,

f = function of ϵ_o, ϵ_1, ϵ_2, and various geometrical parameters, dimensionless,

g = $f/6\pi$ in equation $(2 - 9)$, dimensionless,

K = constant in equation $(4 - 1)$, $volt^{-2}t^{-1}$,

n = amount of suspensoid at anytime,

n_o = amount of suspensoid at initial condition,

p = induced dipole moment, coulomb-cm,

q^+ = induced positive charge, coulomb,

q^- = induced negative charge, coulomb,

r = distance between inner electrode and the centre of gravity of the closer induced charge, cm,

r_o = radius of inner electrode, cm,

Δr = distance between the centres of gravity of induced charges, cm,

R = distance between inner and outer electrodes, cm,

t = residence time for suspension in the filter, min,

u = velocity of suspensoid with respect to medium, cm/min,

v = volumetric flowrate, ml/min,

β = concentration of suspensoid at anytime,

β_o = concentration of suspensoid at initial condition,

ϵ_o = absolute dielectric constant of vacuum, sec/ohm-cm,

ϵ_1 = dielectric constant of suspensoid, dimensionless,

ϵ_2 = dielectric constant of oil, dimensionless,

ϵ_3 = dielectric constant of foam, dimensionless,

θ = additive concentration in suspension, gm/l,

μ = viscosity of oil, centipoises,

ψ = DC voltage difference, volt.

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APPENDIX I

MEASUREMENTS OF POLYURETHANE FOAM

Table I

Physical Property

True specific gravity = 1.10

True density   = 1.10 gm/cm^3

Foam (ppi.) :	80	60	45	30	20	10
Size (cm^3) :	696.41	637.40	680.90	674.40	647.79	697.65
Weight (gm) :	20.279	16.487	22.113	16.194	19.093	19.317
Bulk density (gm/cm^3) :	0.0291	0.0259	0.0325	0.0240	0.0295	0.0277
Porosity (%) :	97.35	97.65	97.05	97.82	97.32	97.48
True volume (cm^3) :	18.44	14.99	20.10	14.72	17.36	17.56
Closed pores (%) :	0.95	0.91	0.68	0.41	0.17	0.15
Apparent porosity (%) :	96.40	96.74	96.37	97.41	97.15	97.33
Surface area (cm^2/cm^3) :	52.82	37.73	26.90	16.73	10.50	4.76

Table II

Actual Residence Time

Length of foam in the filter = 19.05 cm
Diameter of the foam = 5.192 cm
Diameter of the centre rod = 0.314 cm
Bulk volume of the foam = 401.849 cm^3

Foam (ppi.):	80	60	45	30	20	10
Flowrate (ml/min)	Actual residence time, t, in min.					
1085.9	0.357	0.358	0.357	0.360	0.360	0.360
687.6	0.563	0.565	0.563	0.569	0.568	0.569
437.4	0.886	0.889	0.885	0.895	0.893	0.894
322.1	1.203	1.207	1.202	1.215	1.212	1.214
267.5	1.448	1.453	1.448	1.463	1.459	1.462
207.7	1.865	1.872	1.865	1.885	1.880	1.883
148.2	2.614	2.623	2.613	2.641	2.634	2.639
92.7	4.179	4.194	4.178	4.223	4.211	4.219

APPENDIX II

CALIBRATION CURVE FOR FLOWMETER

VOLUMETRIC FLOW RATE, v (ml/min)

METER READING

Viscosity of oil : 0.917 cps
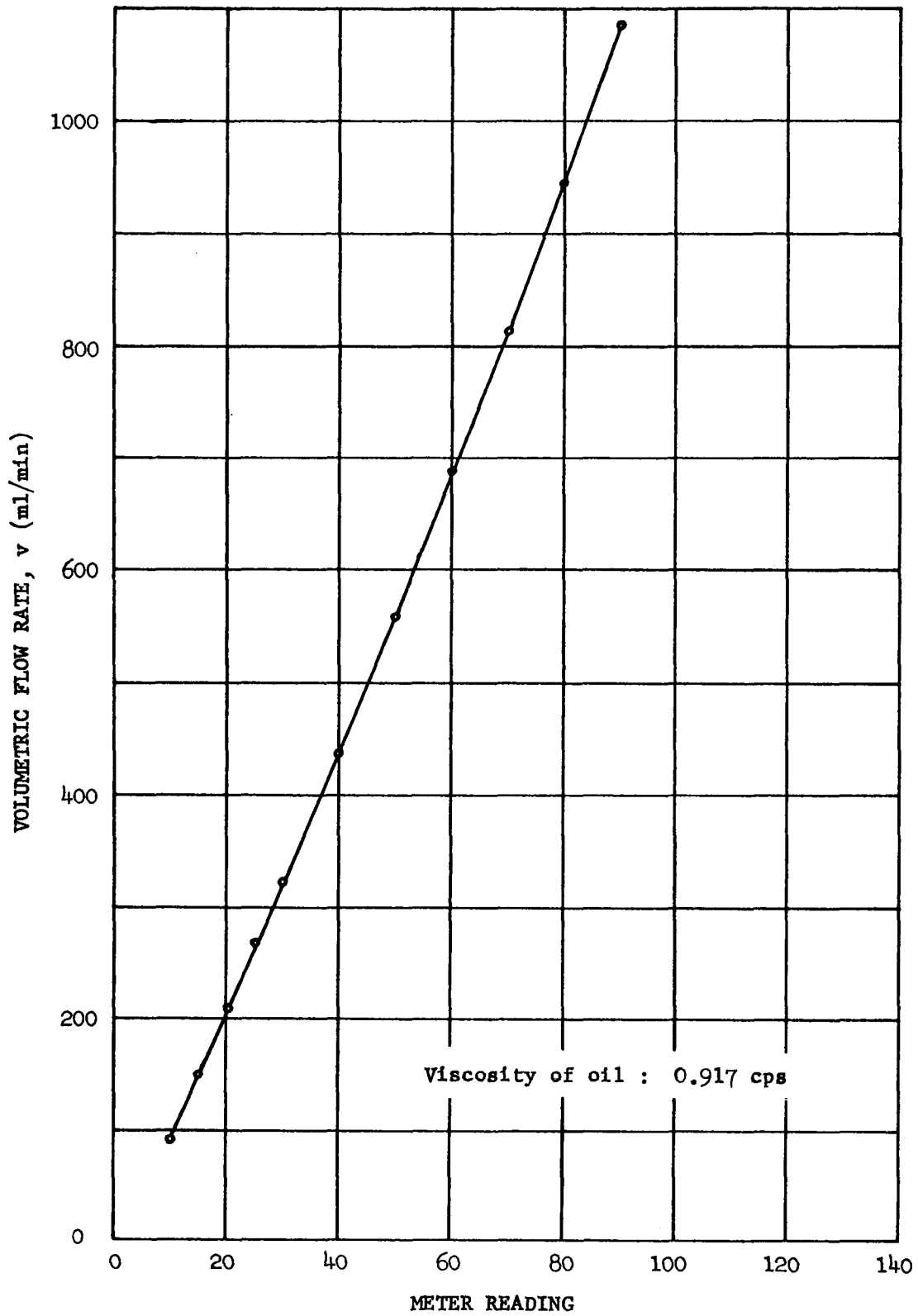
FIGURE 15   CALIBRATION CURVE FOR FLOWMETER

APPENDIX III

EXPERIMENTAL DATA

Table III

Particle Concentration at Outlet of Filter

Flowrate (ml/min)	(A) β	(B) β	(C) β
1085.9	118.8	121.7	66.1
687.6	90.2	109.7	57.6
437.4	51.5	93.5	47.9
322.1	34.7	81.1	39.1
267.5	25.8	71.5	33.4
207.7	15.9	58.6	24.2
148.2	6.0	42.7	13.8

(A) Voltage: 15kv; Foam: 10ppi; Additive concentration: 1.69gm/l;
      Initial concentration β_o: 320.

(B) Voltage: 10kv; Foam: 60ppi; Additive concentration: 0.247gm/l;
      Initial concentration β_o: 170.

(C) Voltage: 10kv; Foam: 45ppi; Additive concentration: 0.863gm/l;
      Initial concentration β_o: 100.

Viscosity of Oil: 0.917 cps.

Table IV

Particle Concentration at Outlet--Initial Concentration Dependence

Initial conc. B_0 :	379.4	285.5	212.4	159.4	121.9	93.4	69.9	54.6
Flowrate (ml/min)	β	β	β	β	β	β	β	β
1085.9	193.6	152.3	113.7	86.2	65.1	49.2	37.7	29.6
687.6	139.4	109.9	86.7	63.6	48.3	36.5	28.0	22.2
437.4	83.8	67.9	54.2	39.5	30.6	23.5	18.0	14.4
322.1	50.4	40.3	32.5	24.1	19.0	14.9	10.9	8.7
267.5	38.3	30.3	23.2	17.1	13.2	10.0	7.8	6.2
207.7	19.8	15.6	11.7	8.5	6.7	5.0	4.1	3.3
148.2	6.4	5.1	3.9	3.0	2.3	1.7	1.4	---

Voltage: 15kv

Foam : 20ppi

Additive conc. : 1.058gm/1

Viscosity of Oil: 0.917cps

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Table V

Particle Concentration at Outlet--Voltage Dependence

Initial conc. β_0 :	38.1	63.0	98.8	137.9	201.7	271.2
Voltage (kv):	6	10	14	18	22	26
Flowrate (ml/min)	β	β	β	β	β	β
1085.9	30.5	36.5	32.3	18.6	11.3	5.9
687.6	27.4	29.9	21.0	9.8	4.1	2.3
437.4	23.9	22.3	10.9	3.3	1.7	---
322.1	22.0	17.0	5.3	1.8	1.1	---
267.5	20.4	13.6	3.4	1.5	---	---
207.7	18.1	8.7	1.9	1.1	---	---
148.2	14.0	4.1	1.1	---	---	---
92.7	8.0	1.2	---	---	---	---

Additive concentration: 1.41 gm/l

Foam : 45 ppi.

Viscosity of Oil : 0.917 cps

Table VI

Particle Concentration at Outlet--Voltage Dependence

Initial conc. β_o :	42.3	69.4	110.1	154.1	208.5	261.8
Voltage (kv):	6	10	14	18	22	26
Flowrate (ml/min)	β	β	β	β	β	β
1085.9	35.5	45.7	43.3	26.8	3.6	2.5
687.6	32.6	39.2	31.1	14.2	2.1	2.1
437.4	30.0	31.4	18.7	5.0	1.8	1.9
322.1	27.9	25.0	11.5	2.9	---	---
267.5	26.1	21.3	7.5	2.4	---	---
207.7	23.9	16.4	4.7	2.1	---	---
148.2	19.9	9.8	2.5	---	---	---
92.7	12.9	3.6	---	---	---	---

Additive concentration: 1.71 gm/l

Foam : 45 ppi.

Viscosity of Oil : 0.917 cps

Table VII

Particle Concentration at Outlet--Additive Concentration Dependence

Additive conc. θ :	2.036	1.761	1.504	1.242	0.994	0.732	0.511	0.247
Initial conc. β_0 :	109.2	100.0	100.0	97.7	100.1	83.6	105.7	89.7
Flowrate (ml/min)	β	β	β	β	β	β	β	β
1085.9	72.7	66.1	59.9	45.5	40.8	22.1	20.7	12.8
687.6	65.1	57.6	51.1	34.7	28.8	12.8	10.1	5.2
437.4	55.2	47.9	39.8	22.8	16.6	5.5	3.6	2.0
322.1	47.5	39.1	29.1	15.8	9.4	2.4	1.7	0.9
267.5	41.2	33.4	23.9	11.5	6.4	1.7	---	---
207.7	33.4	24.2	16.8	6.7	3.4	1.2+	---	---
148.2	20.5	13.8	8.0	2.9	1.7	---	---	---
92.7	7.2	3.9	2.2	---	---	---	---	---

Voltage : 10 kv

Foam : 45 ppi.

APPENDIX IV

CALCULATED DATA FOR DIMENSIONLESS PLOT

The following tables were made according to equation (5 - 4)

shown in Chapter V for all the experimental data taken with 45 ppi.

foam.

[β/β_0] : This dimensionless value was taken experimentally at different residence time, t.

$$[\gamma] = [\frac{\epsilon_2\, \epsilon_0}{\mu}\ e^{-(C\theta)}\ (\psi/R)^2\ (t+B\theta)\ ] :$$ This dimensionless group has the constants, $\mu = 0.917$ cps, $\epsilon_2 = 2.08$, $C = 1.280$ 1/gm, $B = 0.116$ min-1/gm, and $R = 2.596$ cm.

Table VIII-a

Voltage   : 6 kv
Additive conc. : 1.41 gm/l

t :	0.357	0.563	0.885	1.202	1.448	1.865	2.613	4.178
β/β_0:	0.801	0.719	0.627	0.577	0.535	0.475	0.367	0.210
γ :	1.03	1.45	2.08	2.72	3.21	4.04	5.54	8.66

Table VIII-b

Voltage   : 10 kv
Additive conc. : 1.41 gm/l

t :	0.357	0.563	0.885	1.202	1.448	1.865	2.613	4.178
β/β_0:	0.519	0.475	0.354	0.270	0.216	0.138	0.065	0.019
γ :	2.89	4.03	5.80	7.56	8.92	11.23	15.37	24.04

Table VIII-c

Voltage   : 14 kv
Additive conc. : 1.41 gm/l

t :	0.357	0.563	0.885	1.202	1.448	1.865	2.613
β/β_0:	0.327	0.213	0.110	0.0536	0.0344	0.0192	0.0111
γ :	5.65	7.88	11.39	14.83	17.50	22.02	30.13

Table VIII-d

Voltage   : 18 kv
Additive conc. : 1.41 gm/l

t :	0.357	0.563	0.885	1.202	1.448
β/β_0 :	0.135	0.0711	0.0239	0.0133	0.0109
γ :	9.35	13.04	18.81	24.50	28.92

Table VIII-e

Voltage   : 22 kv
Additive conc. : 1.41 gm/l

t :	0.357	0.563
β/β_0 :	0.056	0.0203
γ :	13.96	19.47

Table VIII-f

Voltage : 26 kv

Additive conc. : 1.41 gm/1

t : 0.357

β/β_0 : 0.0218

γ : 19.50

Table VIII-g

Voltage : 6 kv

Additive conc. : 1.71 gm/1

t :	0.357	0.563	0.885	1.202	1.448	1.865	2.613	4.178
β/β_0:	0.839	0.771	0.709	0.660	0.617	0.565	0.470	0.305
γ :	0.76	1.03	1.47	1.90	2.24	2.81	3.81	5.94

Table VIII-h

Voltage : 10 kv

Additive conc. : 1.71 gm/1

t :	0.357	0.563	0.885	1.202	1.448	1.865	2.613	4.178
β/β_0:	0.659	0.565	0.452	0.360	0.307	0.236	0.141	0.0519
γ :	2.10	2.87	4.09	5.28	6.20	7.78	10.60	16.51

Table VIII-i

Voltage   : 14 kv
Additive conc. : 1.71 gm/l

t :	0.357	0.563	0.885	1.202	1.448	1.865	2.613
β/β_0:	0.393	0.282	0.170	0.104	0.0681	0.0827	0.0227
γ :	4.10	5.63	8.01	10.35	12.17	15.26	20.78

Table VIII-j

Voltage   : 18 kv
Additive conc. : 1.71 gm/l

t :	0.357	0.563	0.885	1.202	1.448	1.865
β/β_0:	0.174	0.0921	0.0324	0.0188	0.0156	0.0136
γ :	6.79	9.30	13.24	17.11	20.12	25.21

Table VIII-k

Voltage   : 22 kv
Additive conc. : 1.71 gm/l

t :	0.357	0.563
β/β_0 :	0.0173	0.0101
γ :	10.14	13.90

Table VIII-1

Voltage   : 10 kv
Additive conc. : 2.036 gm/1

t	:	0.357	0.563	0.885	1.202	1.448	1.865	2.613	4.178
β/β_0	:	0.666	0.596	0.505	0.435	0.377	0.306	0.188	0.0659
γ	:	1.47	1.98	2.78	3.56	4.17	5.20	7.05	10.94

Table VIII-m

Voltage   : 10 kv
Additive conc. : 1.761 gm/1

t	:	0.357	0.563	0.885	1.202	1.448	1.865	2.613	4.178
β/β_0	:	0.661	0.576	0.479	0.391	0.334	0.242	0.138	0.0390
γ	:	1.98	2.72	3.84	4.97	5.83	7.31	9.95	15.49

Table VIII-n

Voltage   : 10 kv
Additive conc. : 1.504 gm/1

t	:	0.357	0.563	0.885	1.202	1.448	1.865	2.613	4.178
β/β_0	:	0.599	0.511	0.398	0.291	0.239	0.168	0.080	0.022
γ	:	2.61	3.63	5.20	6.76	7.96	10.01	13.69	21.39

Table VIII-o

Voltage   : 10 kv
Additive conc. : 1.242 gm/1

t :	0.357	0.563	0.885	1.202	1.448	1.865	2.613
β/β_0:	0.466	0.355	0.233	0.162	0.118	0.0686	0.0297
γ :	3.44	4.86	7.07	9.24	10.92	13.79	18.93

Table VIII-p

Voltage   : 10 kv
Additive conc. : 0.994 gm/1

t :	0.357	0.563	0.885	1.202	1.448	1.865	2.613
β/β_0:	0.408	0.288	0.166	0.0939	0.0639	0.0340	0.0170
γ :	4.44	6.45	9.43	12.41	14.72	18.65	25.71

Table VIII-q

Voltage   : 10 kv
Additive conc. : 0.732 gm/1

t :	0.357	0.563	0.885	1.202	1.448	1.865
β/β_0:	0.264	0.153	0.0658	0.0287	0.0203	0.0150
γ :	5.83	8.55	12.79	16.97	20.23	25.72

Table VIII-r

Voltage   : 10 kv
Additive conc. : 0.511 gm/1

t	0.357	0.563	0.885	1.202
β/β_o	0.196	0.0956	0.0341	0.0161
γ	7.28	10.88	16.53	22.06

Table VIII-s

Voltage   : 10 kv
Additive conc. : 0.247

t	0.357	0.563	0.885
β/β_o	0.143	0.0580	0.0223
γ	9.47	14.52	22.42

VITA AUCTORIS

1937 Born on November 12, in Shanghai, China.

1951 Completed elementary education at Fujimizu Public School, Tsu-city, Mie-ken, Japan.

1954 Completed secondary education (Third Form) at Doshisha Junior High School, Kyoto-city, Japan.

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1961 Graduated from Tunghai University, Taiwan, China, with the degree of B.Sc. in Chemical Engineering.

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