UNIVERSITY OF ILLINOIS

MAY 17 19 89

THIS IS TO CERTIFY THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

AMY LEIGH MARKS

ENTITLED CHARACTERISTICS OF THE ELECTRORHEOLOGICAL SUSPENSION STRUCTURES IN ELECTRIC FIELDS

IS APPROVED BY ME AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE

DEGREE OF BACHELOR OF SCIENCE IN CHEMICAL ENGINEERING

Instructor in Charge

APPROVED:

HEAD OF DEPARTMENT OF CHEMICAL ENGINEERING

O-1364

Characteristics of the Electrorheological Suspension Structures in Electric Fields

By

Amy L. Marks

Thesis

for the
Degree of Bachelor of Science
in Liberal Arts and Sciences

College of Liberal Arts and Sciences
University of Illinois
Urbana, Illinois

1989

Abstract

This paper discusses two topics relating to electrorheological suspensions. The first part of the study examines a method to measure the relative polarity of the particles of dielectric constants by measuring the dielectrophoretic velocity of spherical particles in a suspension. Although some data was collected, the technique was not reliable and efficient. The results were not reproducible.

Recent research suggests that the the rheological behavior (such as shear behavior) of ER suspensions depends on the physical form of the suspension. The second part of this study examines the rearrangement of particles into fibrous structures when an external electric field is applied. The average column width and average distance between columns were determined for several parameters. The parameters which were varied in this study were area fraction, the voltage drop, the gap distance between electrodes, the type of solvent used, and the frequency of the electric field. Because the standard deviation was large for the average column width and the average distance between columns, the changes in the values obtained were insignificant. However, certain trends did emerge which were recorded. The widths of these columns usually increased exponentially with increasing area fraction in all the cases studied, although none of the increases were significant.

Table of Contents

Introduction

The discovery of electrorheological fluids (ER fluids) is usually credited to Winslow in 1949 (1). Electrorheological fluids are composed of solid particles suspended in nonpolar fluids. The suspension fluids (i.e., silicon, vegetable, mineral, and halogenated oils) are usually low in conductivity and have dielectric constants which range between 2 and 15 (2). The particle phase in the suspension can be organic (i.e., flour, microcrystalline cellulose, ion exchange resin, and metal soaps) or inorganic (i.e., silica, titania and metal oxides) in nature (2). ER fluids and their responses have received little attention until recently. An electrorheological response of a suspension is characterized by two main effects: the increase in the apparent suspension viscosity under application of an electric field, and the formation of fibers/columns (3). The increase of the viscosity of the fluid under the application of an external electric field is reversible when the field is turned off.

In two recent studies by Marshall et al. (4) and Klingenberg et al. (3), the relative viscosity of the electrified suspension was found to depend on the particles volume fraction and the Mason number. The Mason number is a measure of the relative importance of viscous shear forces to electric polarization forces acting on particles in the suspension. It is defined as
$[\nu_c g / (2 e_0 e_c B^2 E_0^2)]$. Here, ν_c is the viscosity of the continuous phase of the suspension; the macroscopic/apparent shear rate of the

suspension is g, and E_0 is the magnitude of the applied electric field. The permittivity of free space and the dielectric constant of the continuous phase are e_0 and e_c, and B [= $(e_p - e_c) / (e_p + 2e_c)$] is the relative polarity of the particles of dielectric constants e_p (3). Presently, few techniques exist to measure B directly (3-6).

The first section of this paper describes a method to measure the value of B in the suspension. The technique to determine B in this study uses the principle of dielectrophoresis. Dielectrophoresis is defined as
" ... the motion of matter as induced by its polarization in an inhomogeneous electric field" (7). The matter or the spherical particles (which were used in this case) move to the highest field strength in a nonuniform electric field. Without an external electric field presence, colloid (van der Waals and electrostatic) and thermal forces govern the particles interactions (4). D. Klingenberg and C. Zukoski IV have analyzed an ER suspension composed of silica spheres and corn oil, and characterized it as " ... weak flocuated non-brownian particles in the absence of an electric field" (3). Since this study used silica and other inorganic particles suspended in corn oil (or silicon oil), the composition of the suspension was assumed to be similar to Klingenberg and Zukoski's suspension. When an electric field is applied, dipole moments are induced in the particles. The polarity of responding particles must be included in the previous

analysis. A force appears when neutral particles of dielectric constant, e_p, have been placed in a nonconducting dielectric fluid in the presence of an external field. Klingenberg et al. showed that for their system, polarization and viscous forces should dominate colloidal and thermal forces acting on the particles (3). By assuming the geometry of the electric field is two coaxial cylinders and the particles are spherical in shape, the calculations of the dominating forces are greatly simplified. The force of the induced dipole moment of particles in a dielectric field between two coaxial cylinders is:

$$F = -4(\text{ pi})\, e_c\, R^3 B\ [V/\ln(b/a)]\ (r)^{-3} \qquad (8) \qquad \text{Eqn. 1}$$

Here, the dielectric constant of the solvent is e_c; R is the radius of the particle; V is the voltage drop, a is the inner cylinder electrode; b is the outer cylinder electrode; r is the average position of particle; $B = (e_p + e_c)/(e_p - 2e_c)$ and e_p is the dielectric constant of the particle. This force causes the particle to move to the region of highest field strength.

However, the particle is also subjected to a hydrodynamic resistant. The viscous force is:

$$F_H = -6(\text{pi})\nu\, RU \qquad (8) \qquad \text{Eqn. 2}$$

where ν is the viscosity of the medium, and U is the dielectroporetic velocity.

Hence, by treating the suspension as a simple system (i.e., monodisperse suspension of neutrally buoyant uncharged particles, where polarization forces dominate over colloidal and thermal forces (3,4)), the dielectrophoretic velocity can be determined by balancing theses two forces. The resulting velocity of a particle is:

$$U = -2e_c R^2 B \ [V/\ln(b/a)]^2 \ (1/3\nu \ r^3) \qquad (8) \quad \text{Eqn. 3}$$

Thus, by taking into account only polarization and viscous forces, the term B can be calculated for spherical particles by measuring their velocity in a nonuniform coaxial electric field. This technique would be particularly suited for determining the relative polarity of the particles of ER fluids since the environment used to measure the value of B is similar to an ER suspension.

The second part of this study examined the rearrangement of particles into fibrous structures when an external electric field is applied. Little information is known about the physical structure of suspensions in an electric field. What little information is known is that when an external electric field is applied to a random suspension of particles, the particles form chain-like aggregates of fibrous structures that reversibly degrade by shear (1-7). The rheological behavior (such as shear behavior) of ER suspensions was thought to depend on external factors: volume fraction, shear rate, field strength, frequency, and temperature not the physical form of the suspension (1,5,6). Recent research suggests that the suspension characteristics are important. Klingenberg et al. (3) in a study on the steady shear behavior of ER suspension indicates that there is a growing need for detailed descriptions of the suspension which includes information on columns and cross-linking networks. The ability to link the observed microscopic behavior to the material response of the ER suspension would provide needed insight into certain aspects of ER effects such as rearrangement under periodic or continuous deformation. There are many applications for ER fluids which range from clutches, brakes, pumps, and valves to robotic joints and vibration dampers (2,3). The optimum utilization of ER fluids in these and other applications has been limited by poor understanding of the formation and physical properties of ER suspensions. The second part of this study describes the resulting structure of the rearrangement of ER suspensions.

Experimental Procedure

The suspension in this study consisted of either copper or alumina oxides or silica sphere provided by P. A. Industries. These particles were submerged in various oils (corn oil, mineral oil, and polydimethyl sioxane). The silica spheres were of known water content which ranged from 0.3% to 7.0% water by weight. The water content was achieved by equilibration at room temperature. The particles ranged from 1 to 100 micrometers in diameter and had an average diameter of 57 micrometers. The experiments were carried out at room temperature (20 - 26 ^{o}C). In this study, two different electric field configurations were used.

First, two circular electrodes were used to create a nonuniform electric field. This apparatus was used to measure the velocity of particles. One of the electrodes was a copper plate (2.0 cm x 2.0 cm x 0.3 cm) with a hole of 0.5 cm diameter drilled in the center and mounted on a plexiglass base. The second electrode was a platinum wire (0.05 cm in diameter) which was placed directly in the center of the hole on the copper plate. This provided a coaxial cylinder geometry. The gap between the two electrodes in the cell was 2 cm and was filled with the suspension (Figure 1 in Appendix A). The volume fraction used was extremely small. Between 1 and 10 particles were present when the cell filled with the solution. The small dimensions of the apparatus was used in order to keep the amount of voltage applied at a minimum and still attain the necessary high voltage drop.

The velocity of single particles was determined by measuring the distance the particles traveled and dividing by the time it took to move that distance. The distance was measured directly from the monitor connected to the video camera and converting it to its actual length; the time was measured using a stopwatch.

In the second part of this study, the nonaqueous suspensions of particles were located between two parallel electrodes. In order to create a two dimensional system, extremely thin metal strips were used as the electrodes (0.5cm x 9cm x .0001cm). Therefore, only the x and z axes were considered. The electrodes were laid side by side, sandwiched between a slide and a cover slide. The suspension filled the gap between them (Figure 2 in Appendix B).

The average column width and the average distance between the columns were determined for each suspension. The column widths were measured from the beginning of the first particle to the end of the last particle in the column for each case. This width was measured directly from the monitor and converted to its actual size. Two measurements were made for most suspensions: the first was approximately one third the way down from the top electrode, and the other, two thirds the way down. In appendix B, the column widths are listed along with the distances of oil between them and the average distance between the columns. The average distance between strands was measured from the beginning of one column to the beginning of the next column, which is the sum of the width of the first column and the distance of the oil between the first and second column.

The same set-up was used to supply the voltage to both apparatuses. The power was supplied by a 10 V AC function generator. AC voltage dampened any motion due to electrophoresis.

The voltage from this unit was amplified a thousand times and monitored with a digital voltmeter before it was sent to the electrodes. While the precise current was not measured, it was assumed to be negligible. The frequency used ranged from 1 Hz to 10 kHz, and the voltage drop across the electrodes ranged from 200 kV/m to 1000 kV/m. A safety box was installed between the amplifier and the cell in order to drain/ground any leftover voltage when the power was turned off. A video camera with a zoom lens attached enlarged the suspension by approximately 15 times. The camera was used to record the suspension formation in between the electrodes. For a flow chart, see Figure 3 in Appendix B.

Results and Discussion

The first part of this study examined a method for determining B by measuring the dielectrophoretic velocity of suspended particles in a nonaqueous solution. The technique was inefficient and unreliable. Although the migration of particles to the region of highest field strength was observed, the particles exhibited a random circular motion for the majority of the experiments conducted. For the latter case, the particles rarely reached the surface of the electrode but continually oscillated between them. Several parameters were varied in order to identify and eliminate the cause of this random circular motion. Both AC and DC voltages were used; the voltage drop was varied between 200 kV/m to 1000 kV/m at frequencies ranging from 10 Hz to 10 kHz. Different solvent types (corn oil, mineral oil, and silicon oil) and different particles types (silica, flour, copper and alumina oxides) were tried. The particle was even submerged in the oil at different depths. None of the variations eliminated the random motion. (However, lowering the voltage drop did slow down the motion.) The size of the electrodes was reduced three times. The last reduction in the electrodes' dimensions did temporarily eliminate the random circular motion. From an error analysis done on the calculation of B, using the integrated form of equation 3 in the introduction, the determination of the particle's radius, R, was found to contribute the most to the error in the B value. In order to increase the accuracy of the calculation, BR^2 was determined not B. The total distance the particles traveled was divided up into equal sections. For each section, BR^2 was determined. Between two and five BR^2 values were calculated for each particle depending on the length it traveled. Tables 1 and 2 in the Appendix A list each individual BR^2 of a run, the average BR^2 for a run, and the standard deviation associated with it for copper and alumina particles suspended in corn oil. Since the results obtained were not reproducible, no further elaboration is given.

Recently, studies suggest that the ER responses are related to the suspension structures (2-4). The remaining sections of this paper analyze the structure of the fibers formed when an electric field is applied to an ER suspension. The average column widths and distance between fibers along with the area fractions are listed in Table 3 of Appendix B. Below 20% area fraction, not enough particles existed to form columns which span the gap between electrodes. Above 70% area fraction, the columns had such a large percentage of cross linking it become difficult to determine the start and end of columns; in rare cases, values were determined to a maximum of 85% area fraction. To determine the area fraction, the average column width of a suspension was multiplied by the number of columns formed in the viewing area. This was divided by the height and the length of the visible suspension. The percent of error associated with area fraction values was determined to be approximately 80%. The main source of error came from the error due to averaging the column widths. The error in measuring each individual column width was 3×10^{-5} m. The standard deviation of the average column width was much larger than this value. This was because the series of particles which span the gap between electrodes were not consistently the same width. Columns ranging from one to four particles wide were observed for all area fractions. Although at low area fraction, thick columns were less frequent than at high area fraction. The standard deviation of the average fiber width and the average distance between columns are listed in Table 3B of Appendix B for roughly half of the experiments conducted. The standard deviation of average column width was calculated from these values and is also listed in Table 3B. The average standard deviation for the average column width was calculated as 1 x 10^{-4} m and the average standard deviation for the average distance between columns was 2 x 10^{-4} m.

The parameters which were varied in this study were the voltage drop, the gap distance between electrodes, the type of solvent used, and the frequency of the electric field. A summary of the experimental conditions is listed in Table 4.

Table 4: Summary of Experimental Conditions

EXP.#	Voltage Drop (kV/m)	Electrode Gap Distance (mm)	Solvent Type	Frequency (Hz)
1-4, 15-17	500	1.5	Silicon Oil	10 (1,2,3)
5-14	350	1.6	Silicon Oil	10 (1,3)
18-30	700	1.5	Corn Oil	10 (3)
31-39	500	2.3	Corn Oil	10 (1,2,3)
41-52	500 [4]	1.7	Corn Oil	10 (1,2)

1 Electric field started at 10 Hertz.
2 Electric field started at 100 Hertz which was reduced to 10 Hz.
3 Electric field started at 100 Hertz which was reduced to 10 Hz.
4 Exp. # 42-46 were run at 480 kV/m.

The voltage drop of the suspension was varied between the parallel plate electrodes. Experiments were conducted for the voltage drops of 350 kV/m, 500 kV/m, and 700 kV/m for a voltage drops of 350 kV/m, 500 kV/m, and 700 kV/m for a suspension of silica sphere in polydimethyl sioxane oil at 10 Hz. For each case, the average column width for various area fractions were calculated. Figures 4, 5, and 6 show the relation between the average column width for 350 kV/m, 500 kV/m, and 700 kV/m, respectively. Table 5 lists the average column width for selected area fractions of 0.20 to 0.70.

TABLE 5: Average Column Width for Various Voltage Drops at Selected Area Fractions

AREA FRACTION	EXP.# 5-14 (350 KV/M)	EXP.# 1-4,15-17 (500 KV/M)	EXP. # 18-30 (700KV/M)
0.2	9.00E-05	1.30E-04	6.00E-05
0.3	1.10E-04	1.40E-04	8.20E-05
0.4	1.30E-04	1.60E-04	1.10E-04
0.5	1.40E-04	1.80E-04	1.50E-04
0.6	1.60E-04	2.00E-04	2.10E-04
0.7	1.90E-04	2.30E-04	2.90E-04

In all three cases, the average column width increased with increasing area fraction, but the increase was not significant. None of the changes in the average fiber width for different voltages were significant, and no trend seemed to exist for an increase of the voltage drop at given area fractions. From the data obtained, the average column width appeared to increase with increasing area

Figure 4: V = 350 kV/m, z = 1.6 mm, Silicon Oil

Data from Exp.#5-14

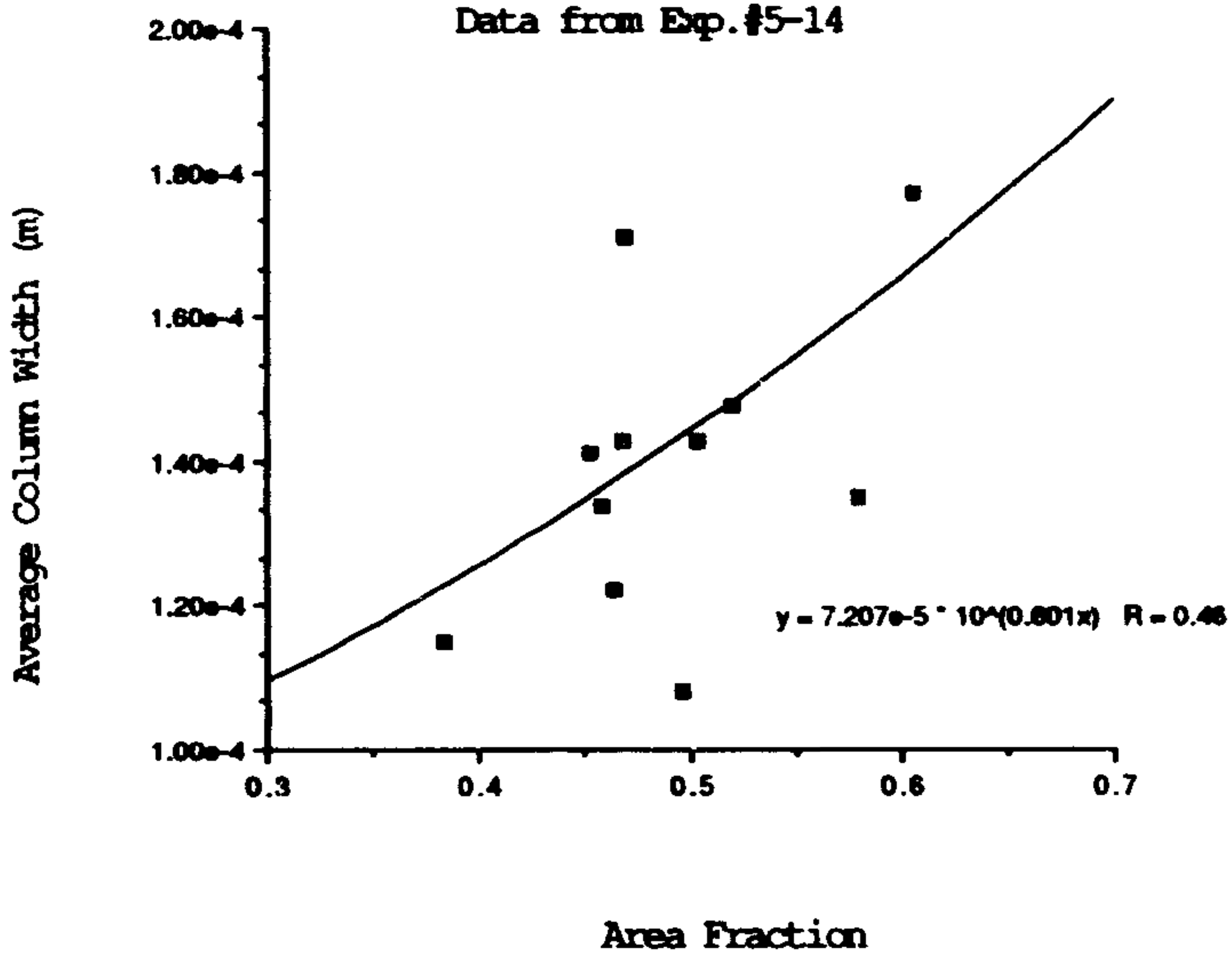


Figure 5: V = 500 kV, z = 1.5mm, Silicon Oil

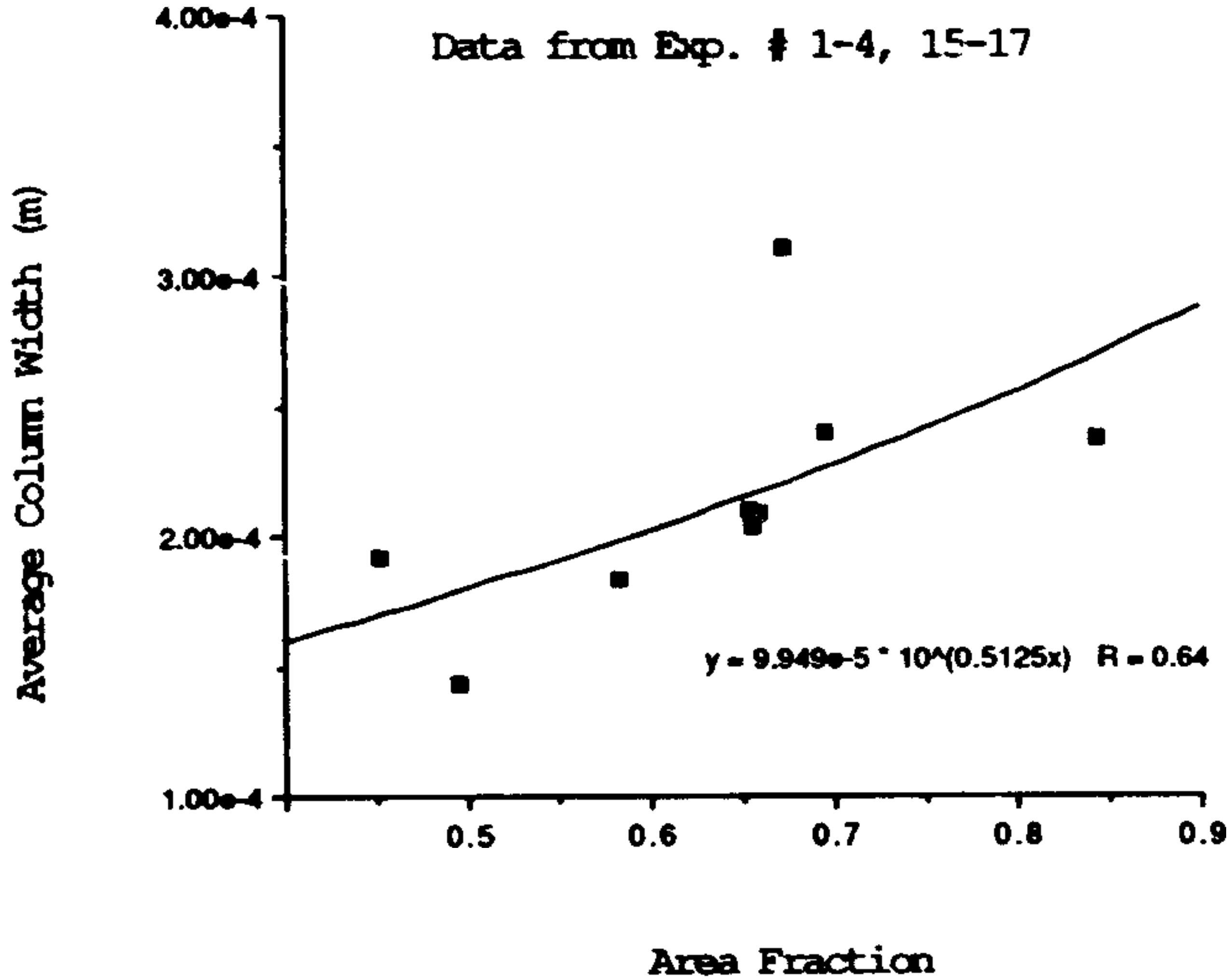
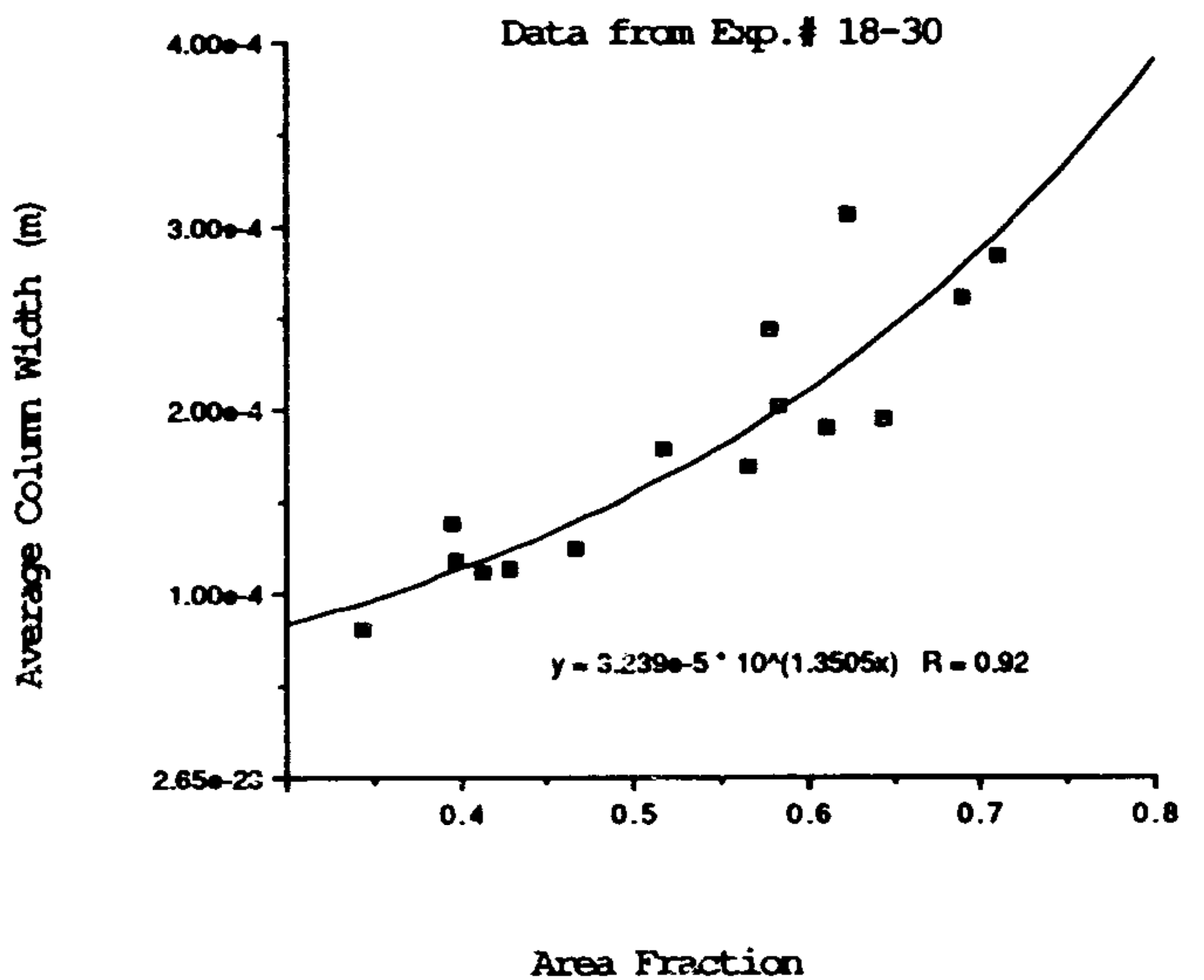


Figure 6: V = 700 kV/m, z = 1.5 mm, Silicon Oil



widths of the suspensions may be independent of the voltage drop between the electrodes .

The average distances between columns were also determined. Table 6 lists the average distances for various area fractions.

TABLE 6: Average Distance Between Column for Various Voltage Drops at Selected Area Fractions

AREA FRACTION	EXP.# 5-14 (350 KV/M)	EXP.# 1-4,15-17 (500 KV/M)	EXP. # 18-30 (700KV/M)
0.2	3.20E-04	3.50E-04	2.00E-04
0.3	3.20E-04	3.50E-04	2.40E-04
0.4	3.10E-04	3.50E-04	2.80E-04
0.3	3.10E-04	3.50E-04	3.20E-04
0.6	3.00E-04	3.50E-04	3.60E-04
0.7	3.00E-04	3.50E-04	4.00E-04

Graphs 7, 8, and 9 show plots of the average distance between columns versus the area fraction for 350 kV/m, 500 kV/m, and 700 kV/m, respectively. Graph 8 showed no change in column spacing with increasing area fraction while in graph 7, the average column spacing decreased slightly, and in graph 8, it increased with increasing area fraction. None of the values changed significantly

Figure 7: V = 350 kV/m, z = 1.6 mm, Silicon Oil

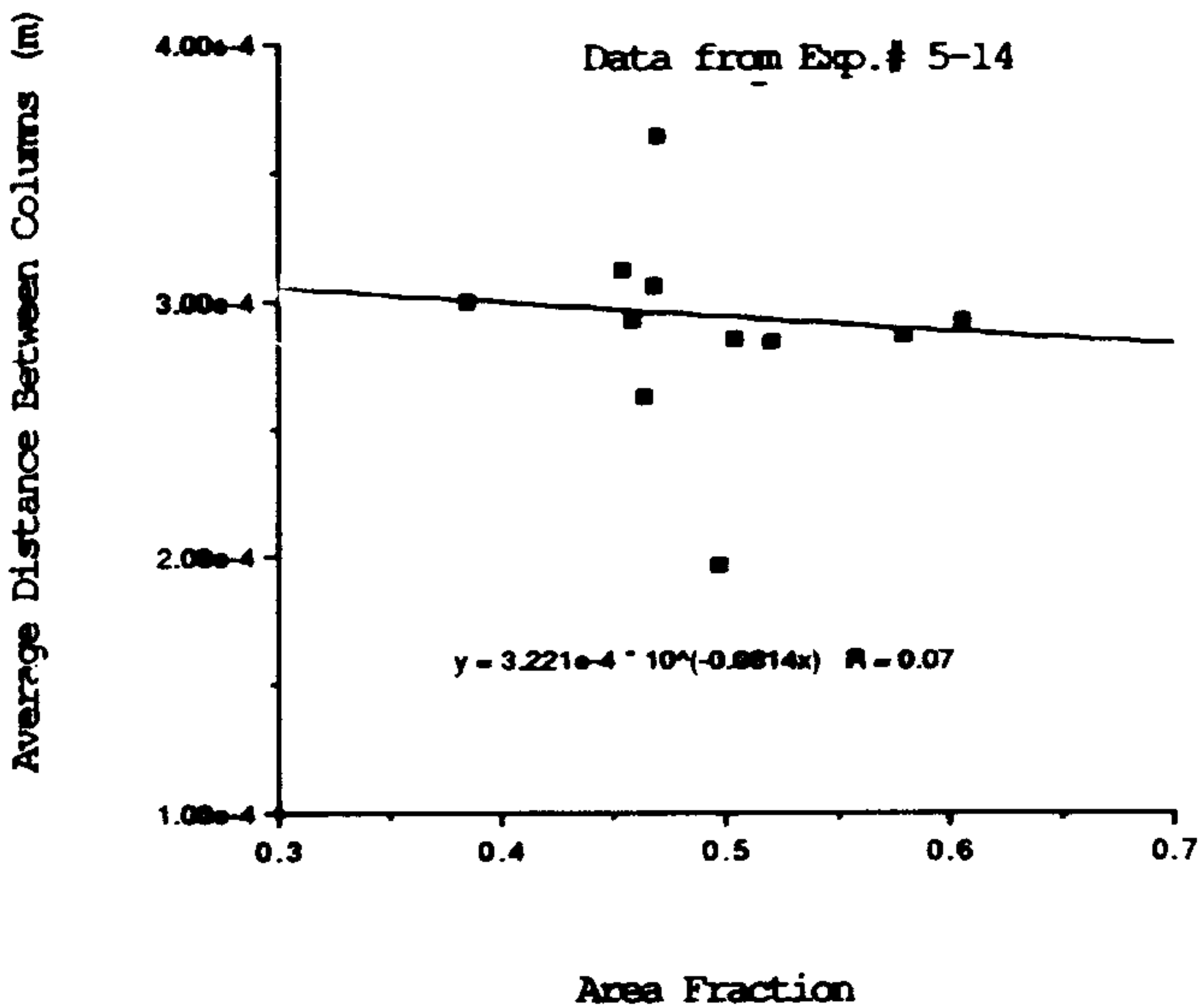


Figure 8: V = 500 kV/m, z = 1.5 mm, Silicon Oil

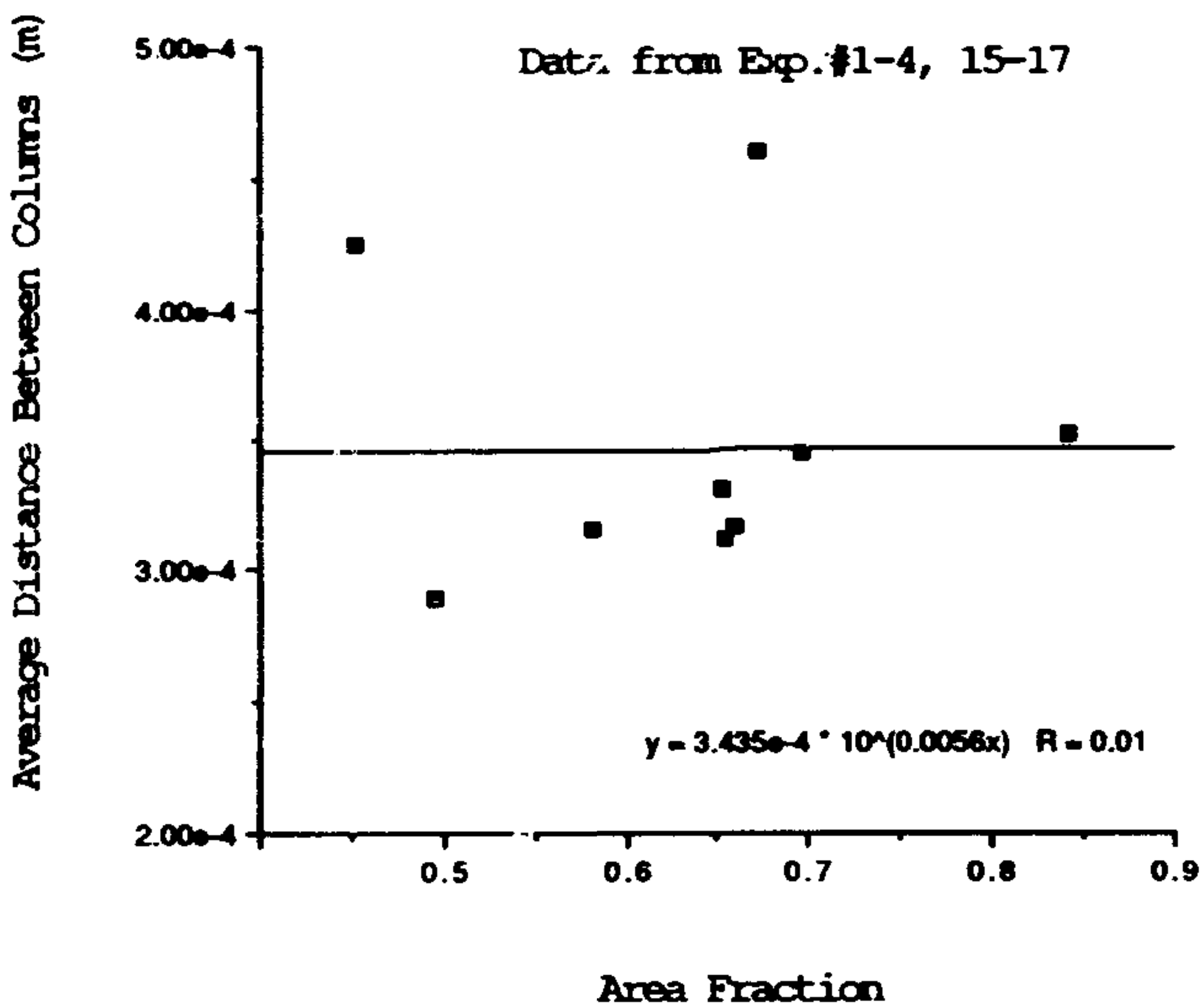
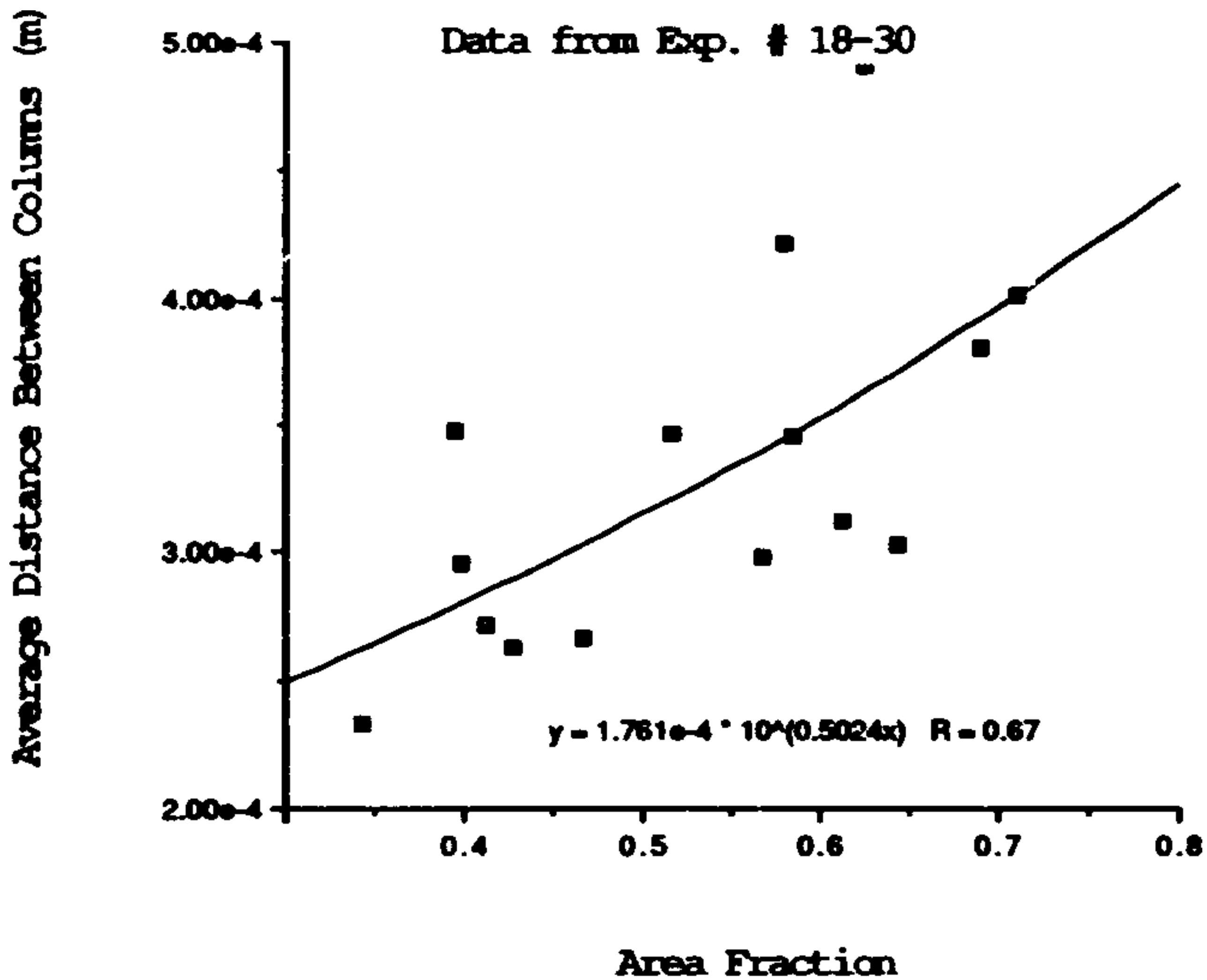


Figure 9: V = 700 kV/m, z = 1.5 mm, Silicon Oil



increasing area fraction. None of the values changed significantly with a change in area fraction or the change in voltage drop. Thus, the average distance between columns was assumed to remain constant (i.e., independent of area fraction or voltage drops). The average spacing between fibers seemed to be constant (i.e., periodic in nature). If the spacing between fibers did not decrease with area fraction, the column widths must have increased with increasing area fractions which graphs 4, 5, and 6 indicate (although the actual increases in the fibers' widths were not significant).

No quantitative data was recorded for the time the particle took to form a relatively static suspension in the presence of an external electric field. From a qualitative analysis of the videotapes, the rearrangement of particles seemed to take a smaller amount of time for high voltages than at low voltage drops. Once a static suspension formed, the voltage could be increased, decreased and even turned off without causing any change in the existing structure.

The effect of the gap distance between the two parallel plate electrodes was also studied for a silica suspension in corn oil at 500 kV/m and 10 Hz. Two similar apparatuses were constructed: one had the parallel plate-like electrodes separated by 2.3 mm and the other, 1.7 mm. The structure of the resulting suspension was examined by the same method which was described previously. Figure 10 and 11 show the relationship between the area fraction and the average column widths. The average column widths for the

Figure 10: V = 500kV/m, z = 2.3 mm, Corn oil

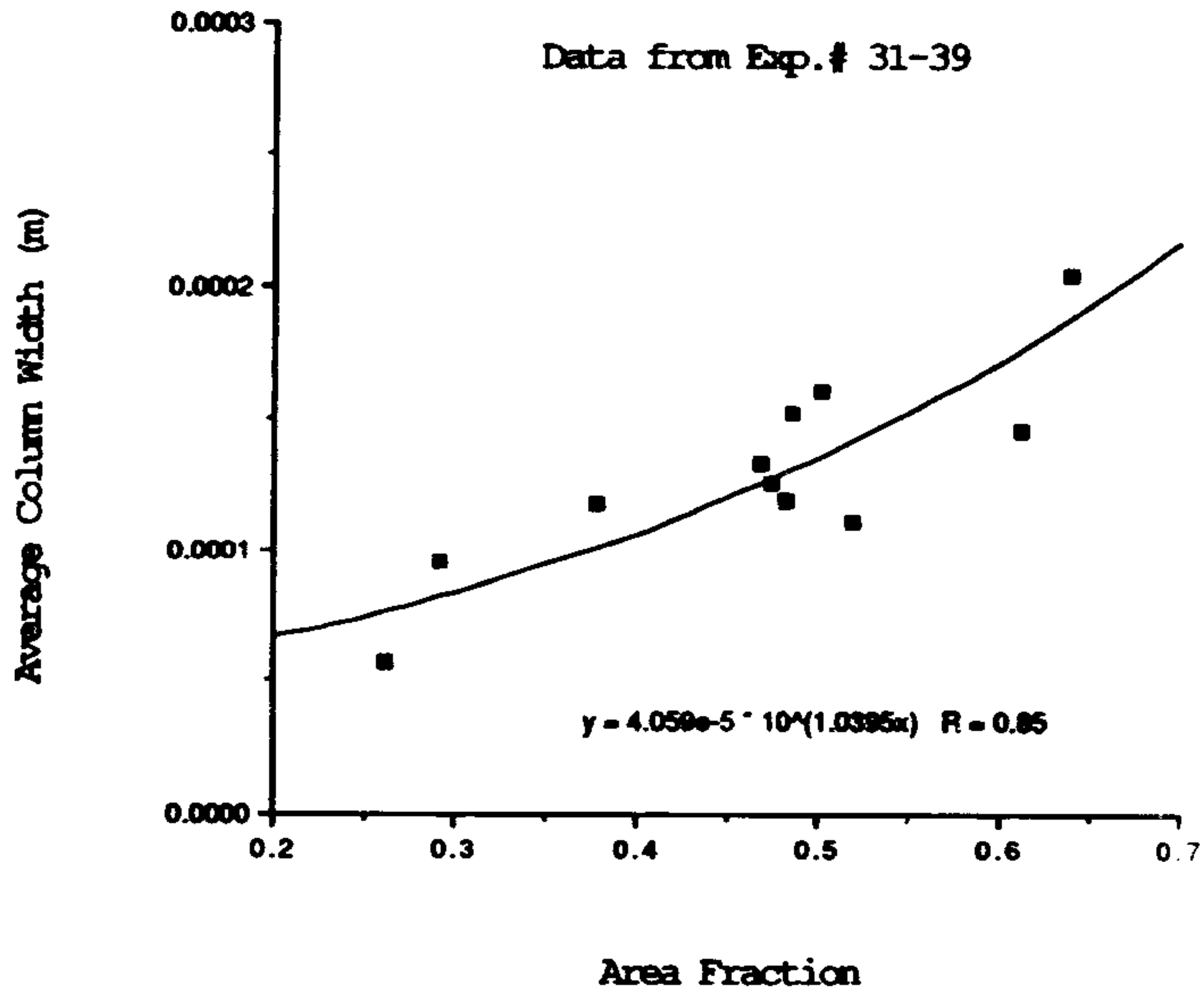
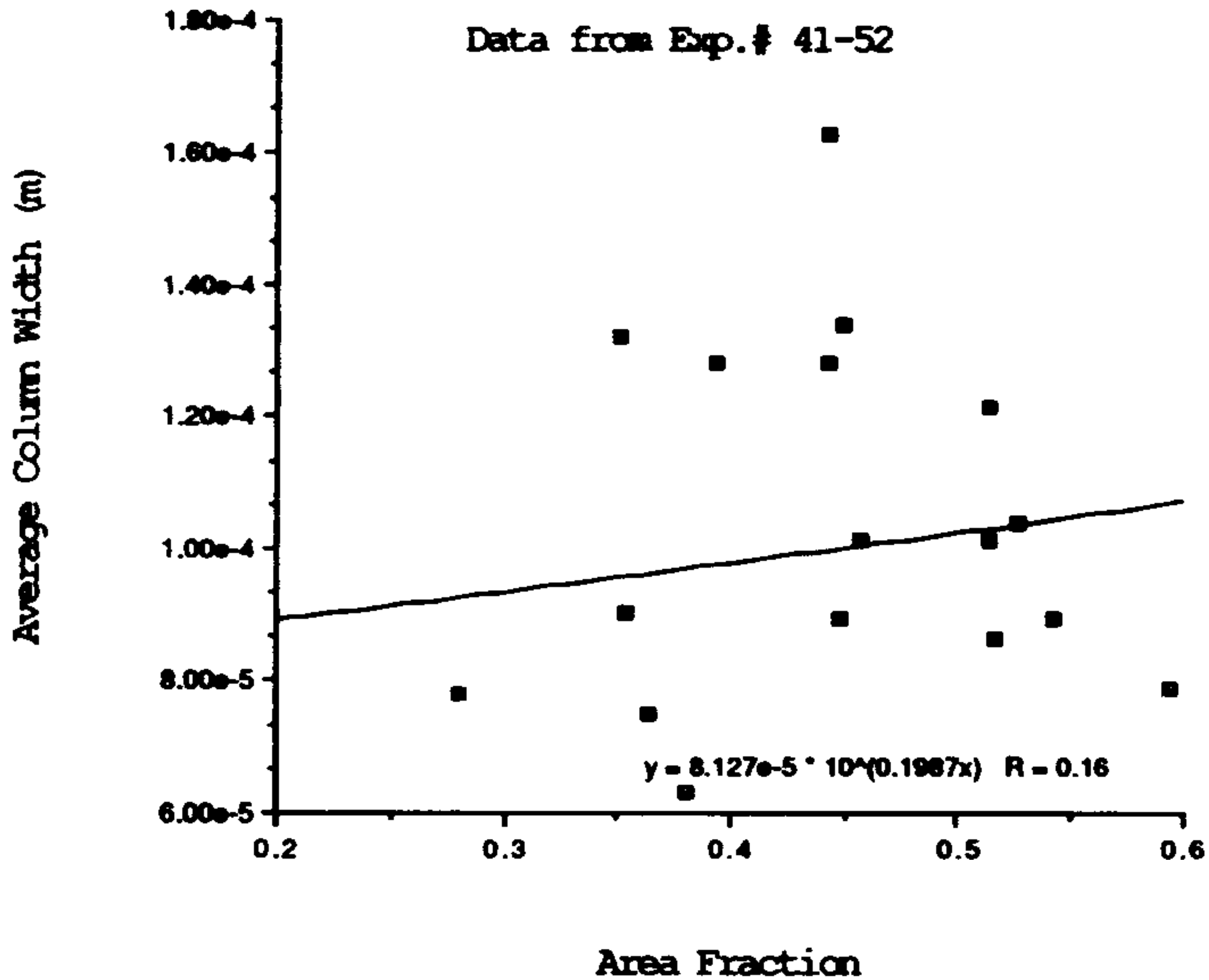


Figure 11: V = 500 kV/m, z = 1.7 mm, Corn Oil



smaller gap size was slightly larger than for the 2.3 mm gap distance for low area fractions, but was smaller for large area fractions. Since no trend was found and the differences between the values were insignificant, the average column width appears to be independent of the electrode gap size. Table 7 lists the average thicknesses of the fibers for selected area fraction.

TABLE 7: Average Column Width for Various Electrode Gap Sizes at Selected Area Fractions

AREA FRACTION	EXP.# 41-52 (L = 1.7 mm)	EXP. # 31-39 (L = 2.3 mm)
0.2	8.90E-05	6.50E-05
0.3	9.30E-05	8.10E-05
0.4	9.60E-05	1.05E-04
0.5	1.02E-04	1.30E-04
0.6	1.07E-04	1.70E-04
0.7	1.13E-04	2.10E-04

The average column width did increase with the area fraction for both cases (the increases were not significant).

From an analysis of the distance between columns over the the area fraction interval of 0.2 and 0.7 for both electrode gap sizes, the column spacing appeared to be constant. The average distance between columns fluctuated between 2.7×10^{-4} m and 3.5×10^{-4} m for both gap sizes as seen in Table 8.

TABLE 8: Average Distance Between Column for Various Electrode Gap Sizes at Selected Area Fractions

AREA FRACTION	EXP.# 41-52 (L = 1.7 mm)	EXP. # 31-39 (L = 2.3 mm)
0.2	3.40E-04	2.70E-04
0.3	3.00E-04	2.70E-04
0.4	2.50E-04	2.80E-04
0.5	2.10E-04	2.90E-04
0.6	1.70E-04	2.90E-04
0.7	1.30E-04	3.00E-04

The distance between columns seemed to be independent of the distance between electrodes.

From an analysis of Figures 12 and 13, no dependence can be detected between area fraction and average distance between columns. For increasing area fraction, Figure 12 shows an increase in the average column spacing while Figure 13 shows a decrease in the average column spacing. No trends were exhibited, and all the changes in the average distance between columns were insignificant. The average distance between fibers fluctuated over the same range for both electrode gap sizes which indicates that the average spacing of columns may be independent of the electrode spacing.

Figure 12: V = 500 kV/m, z = 2.3 mm, Corn Oil

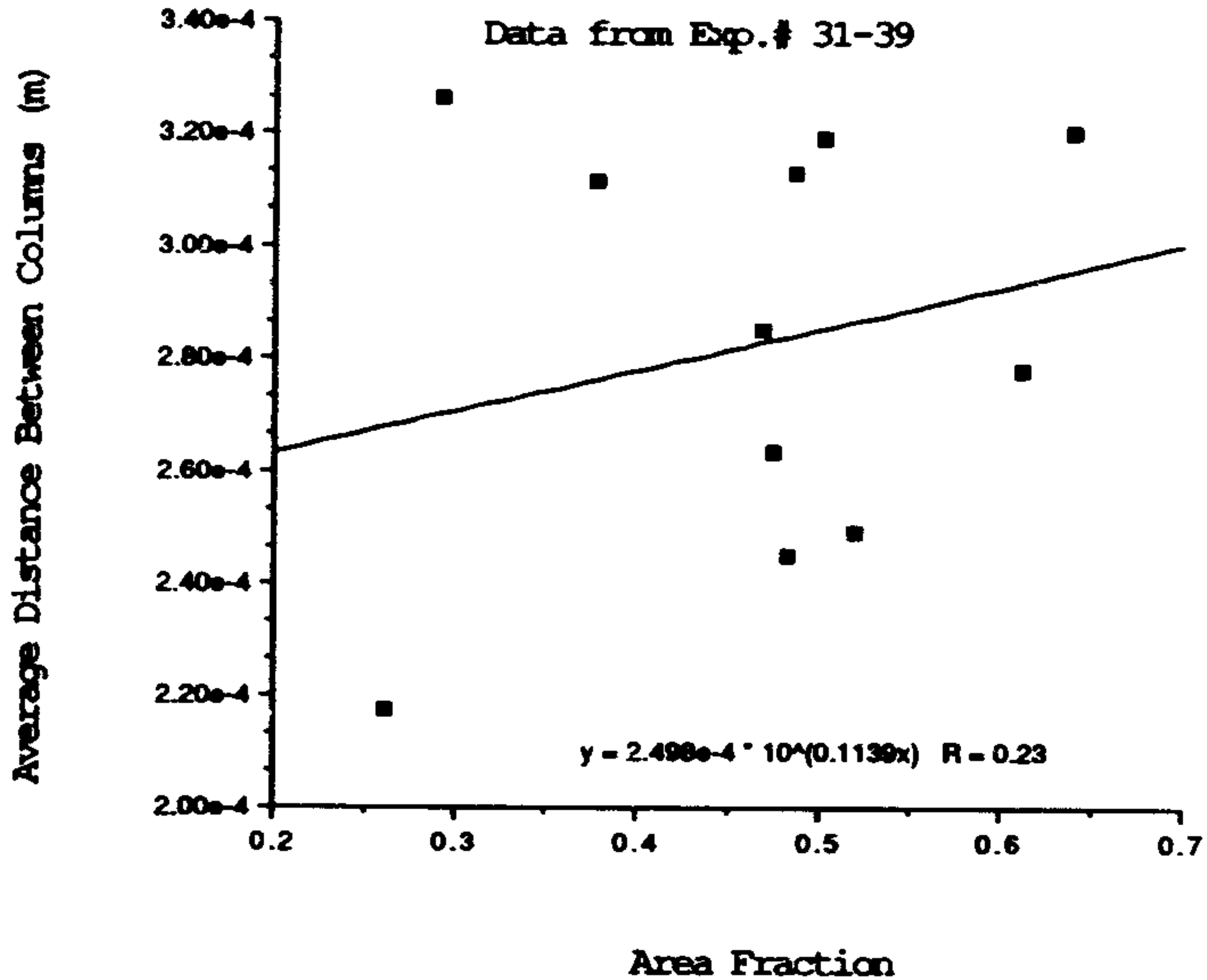
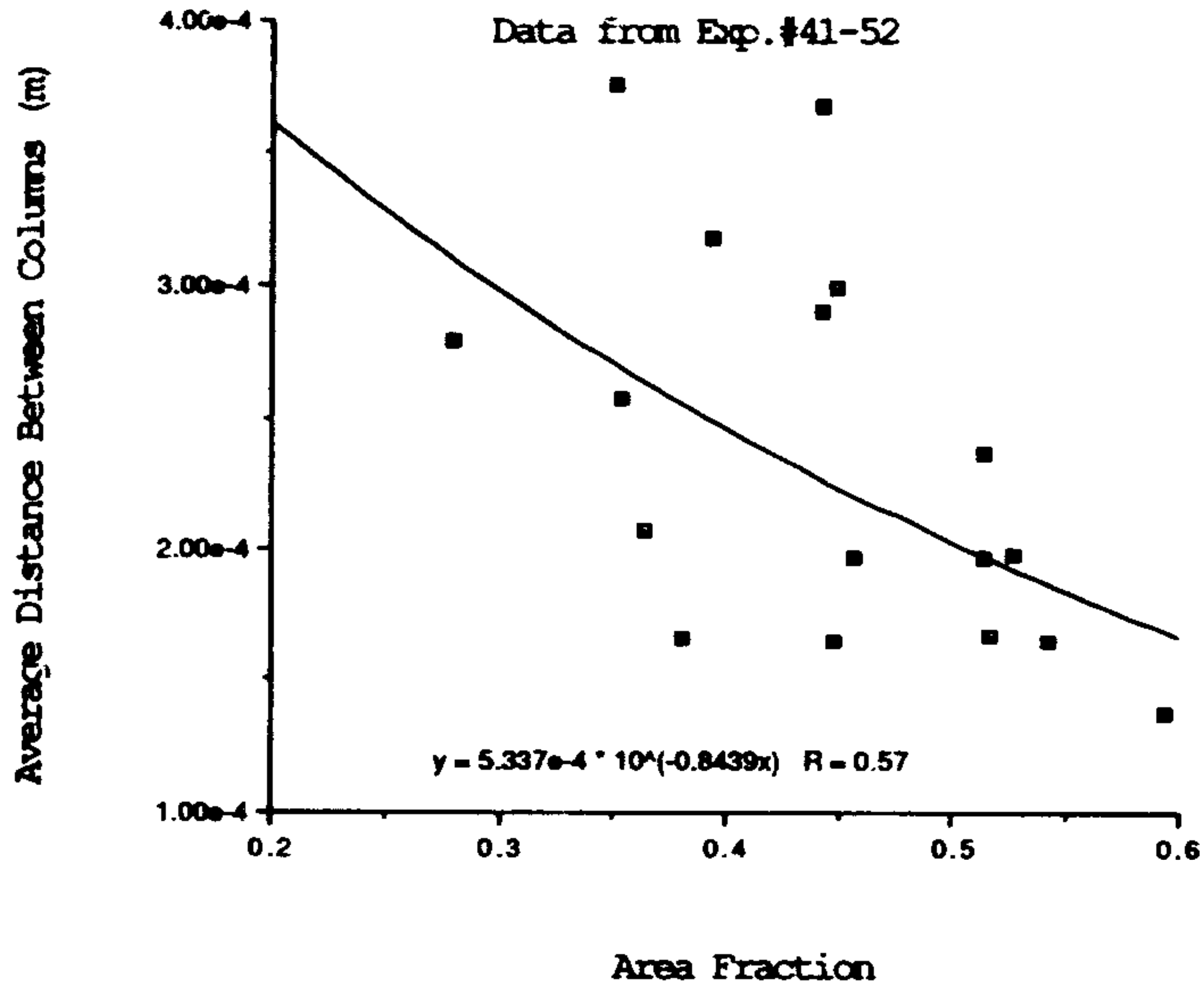


Figure 13: V = 500 kV/m, z = 1.7 mm, Corn Oil



Two different types of solvent were used in the suspension: silicon oil and corn oil. Table 9 lists the average column width for both oils and for six area fractions.

TABLE 9: Average Column Width for Different Suspension Fluids at Selected Area Fractions

AREA FRACTION	EXP.# 1-4,15-17 (Silicon Oil)	EXP. # 41-52 (Corn Oil)
0.2	1.30E-04	8.90E-05
0.3	1.40E-04	9.30E-05
0.4	1.60E-04	9.60E-05
0.5	1.80E-04	1.02E-04
0.6	2.00E-04	1.07E-04
0.7	2.30E-04	1.13E-04

Figures 5 and 11 were the corresponding graphs for silicon and corn oil, respectively. From Table 9, the average column formed in the silicon oil appeared to be wider than columns formed in corn oil (the differences recorded are not significant). Thus, the liquid phase of the suspension may influence the formation of columns when an electric field is applied. Also the average column width for both systems increased with area fraction as was illustrated in all of the graphs previously. Table 10 shows the results for the relationship between average distance between columns and area fraction.

TABLE 10: Average Distance Between Column for Different Suspension Fluids at Selected Area Fractions

AREA FRACTION	EXP.# 1-4, 15-17 (Silicon Oil)	EXP. # 41-52 (Corn Oil)
0.2	3.50E-04	3.40E-04
0.3	3.50E-04	3.00E-04
0.4	3.50E-04	2.50E-04
0.5	3.50E-04	2.10E-04
0.6	3.50E-04	1.70E-04
0.7	3.50E-04	1.30E-04

No change was observed in the silicon oil suspension while the average distance between columns decreased with area fraction for the corn oil suspension. This is illustrated in Figures 8 and 13. The plots also show that the values of the average distance between columns in the silicon oil were smaller than the average distances in corn oil. This indicates that the columns were spaced closer together when the suspension fluid was silicon oil rather than corn oil. However, even the largest discrepancy between the values of the column spacing of the two oils was not significant.

Figure 14 and Figure 15 are pictures of the silica particles suspended in silicon oil at an area fraction at 55% before and after

Figure 14

Experiment 23, No Electric Field,

z = 1.6 mm, Silicon Oil, Silica Spheres.

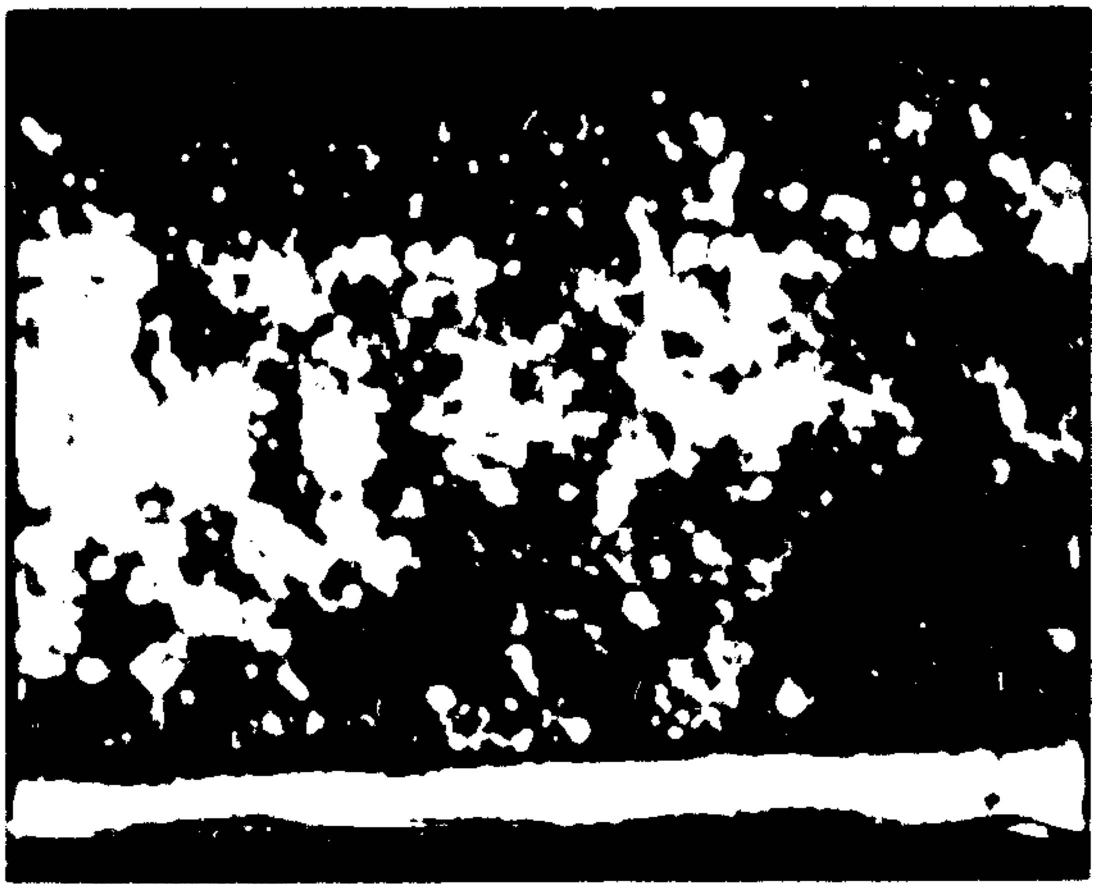


Figure 15

Experiment 23, 700 kV/m,

z = 1.6 mm, Silicon Oil, Silica Spheres.

being exposed to an elect ꞉ fie.d. T esulting growth of groups of chains from the electrode walls forms strands is illustrated in Figure 15. Cross-li(r)king and columns (˝ various widths can be observed in this figure.

The frequency of the electric field applied was also changed. The stability of the formation qualitatively appeared dependent on the frequency. When an electric field was applied to a suspension at low frequency (1 -10 Hz) the particles rearranged to form fibers. Once relatively static structures were constructed, the frequency could be increased or decreased without changing the formation of the columns. (Some charged particles did exist in the suspension and would oscillate at low frequencies. Since their number was small compared to the total number of particles in the suspension, they were neglected and not included in this qualitative analysis.) However, if the formation of columns took place at high frequencies (1 kHz and above), the suspension became dependent on the frequency to a certain degree. When the frequency was lowered after the relatively static structures were formed, the particles would rearrange again to form slightly different fibrous structures. The movement of particles in the second formation was usually not as drastic as the first arrangement. The second resulting suspensions appeared to have less cross-linking and included less single or small clusters of particles, which did not attached to columns. After the second reformation of the fibers became static, the frequency became independent of frequency (as if it was formed at low frequencies). Raising or lowering the frequency (even below the value which caused the second rearrangement) did not change the system. The frequency at which the second rearrangement started seemed to depend on the electrode gap size. The maximum frequency which created the reformation was 10 Hz for the electrode separated at 1.7 mm and was 1 Hz for the separation of 2.3 mm. The reformation would happen at values lower than these, but not higher (i.e., for 1.7 mm electrode gap, the reformation of columns took place at 1 Hz if 10 Hz was not tried first). No noticeable dependence was found between the frequency at which the second rearrangement started and the voltage drop, area fraction, or solvent type.

The fibers were less cross-linked and better defined after the second formation. For the majority of the experiments, the electric field was applied at high frequencies (due to the fact the the dielectric constant is dependent on the frequency and high frequency was more desirable), but the amount of the hertz was lowered in order to obtain better formation of columns. Both formations were recorded on videotape. Since the suspension fibers were clearer and much easier to measure at low frequencies, most of the results attained were at low frequencies (i.e., systems starting at low frequencies or ones which were switched to a low frequency after starting at a high one) as shown in Table 4.

The second part of the study analyzed the structure of the fibers formed when an electric field is applied to an ER suspension and gave the average column width and the average distance between fibers for area fractions between 0.20 and 0.70. The standard deviation was very large for both the average column width and the average distance between fibers. Thus, all the changes recorded were insignificant. However, several trends did emerge which were mentioned above.

Conclusions and Recommendations

B, [$= (e_p - e_c)/(e_p + 2e_c)$], the relative polarity of the particles of dielectric constants e_p, cannot be determined reliably and efficiently by measuring the dielectrophoretic velocity of spherical particles in a suspension. Although some data was collected, the experimental results were not reproducible. Further study of this method would prove to be fruitless. Therefore, it is recommended that other methods should be developed.

Applications of an external electric field induces polarization forces between the particles in a suspension and result in columns of particles spanning the electrode gap. The widths of these columns usually increase exponentially with increasing area fraction in all the cases studied, although none of the increases were significant.

No noticeable trend was detected between the average strand width and the voltage drop (which was studied at 350 kV/m, 500 kV/m, and 700 kV/m) or the parallel plate electrode gap distances.

Silica particles suspended in silicon oil formed consistently wider average strands than fibers formed in corn oil. However, all differences recorded between the two oils were insignificant.

The average distance between columns was also studied for changes in area fraction, voltage drop, electrode gap distance, and solvent type. The average distance between columns increased, decreased, and remained constant for increasing area fractions in the cases studied. Since no trends seemed to exist and all the differences were insignificant, the average distance between columns was assumed to be independent of area fraction. This would support the earlier conclusions that the average column width increases with increasing area fraction (although none of the increases were significant).

The interval over which the average distances between strands fluctuated was the same for all three voltage drops applied. This indicates that the spacing between columns is independent of the voltage drop.

The average distance between columns was smaller for the smaller electrode gap distance, and for the suspension fluid of silicon oil. These differences were not significant and only two cases were studied for each parameter. Therefore, no conclusion was made regarding the dependence of the average distance between columns for different electrode gap sizes and different solvent types.

A second rearrangement of strands was observed for suspensions which were exposed to an electric field at high frequencies and then to low frequencies. Due to the difficulty in measuring the fiber width for suspensions formed in electric fields at high frequencies, no quantitative data was obtained. Qualitatively, the second formation appeared to be relatively independent of changes in voltage drop and solvent type, but dependent on the electrode gap size.

Because the standard deviation was large for both the average column width and the average distance between columns, the changes in the values obtained were insignificant. However, certain trends did emerge which were recorded.

Further study of the characteristics of particle rearrangement is needed. If a method of analyzing the average column width and average distance between columns could be found that had a lower standard deviation, more conclusive results could be obtained. A more detailed study of the formation of strands and their dependence on electrode gap size, solvent type, and frequency should be conducted. Also, a method that would allow accurate determination of the reformation time should be devised; the determination of the time by means of videotaping the rearrangement of suspensions was quite difficult due to the speed of the fiber formations. The information gathered from these studies would provide further insight into electrorheological effects.

References

1. Winslow, W. M., "Induced Fibration of Suspensions," J. of Applied Physics, 20, (1949), 1137-1140.

2. Gast, A. P. and Zukoski, C. F., "Electrorheological Fluids as Colloidal Suspensions," submitted to Advances in Colloid and Interface Science, October (1988).

3. Klingenberg, D. J., and Zukoski, C. F., "Studies on the Steady Shear Behavior of Electrorheological Suspensions," submitted Langmuir, (1988).

4. Marshall, L., Goodwin, J.W., and Zukoski C.F., "The Effects of Electric Fields on the Rheology of Concentrated Suspensions," accepted for publication in Faraday Transaction I (1988).

5. Klass, D. L., and Martinek, T. W., "Electroviscous Fluids. I. Electric Properties," J. of Applied Physics, 38, (1967), 64-74.

6. Klass, D. L., and Martinek, T. W., "Electroviscous Fluids. II. Electric Properties," J. of Applied Physics, 38, (1967), 75-80.

7. Pohl H. A., Dielectrophoresis: The behavior of neutral matter in nonuniform electric fields, Cambridge University Press, Chambridge, (1978).

8. Klingenberg, D. J., University of Illinois at Urbana-Champaign, working paper, (1989).

Acknowledgement

The author would like to thank C. F. Zukoski IV for his guidance and insightful suggestions. A. L. M. would also like to thank D. J. Klingenberg for his helpful discussion and Michael Westjohn for his help and time.

Appendix A:

Beta Calculations

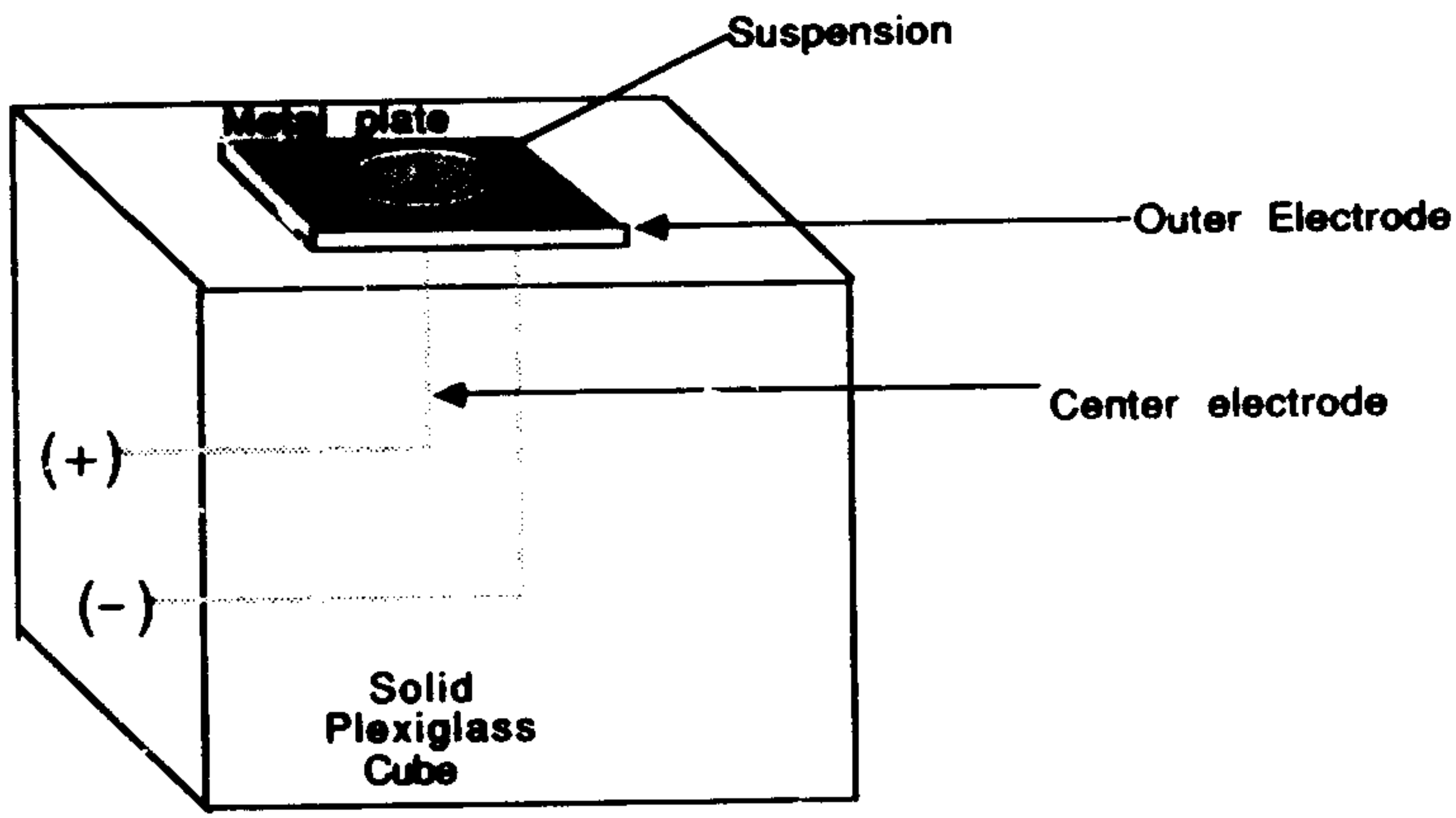


Figure 1: A Suspension between Coaxial Electrodes.

Table 1: BR^2 Values for Copper Oxide Particles in Corn Oil

Exp.#	Individual BR^2	Average [illegible]R^2	Standard Deviation
1	1.7669E-09		
	2.5489E-09		
	3.5247E-09		
	5.0527E-09	3.2233E-09	1.4158E-09
2	1.7669E-09		
	2.5489E-09		
	2.5682E-09		
	3.6532E-09	2.6343E-09	7.7505E-10
3	1.7319E-09		
	2.2078E-09		
	2.6481E-09		
	3.1125E-09	2.4251E-09	5.916E-10
4	7.1397E-10		
	1.1157E-09		
	1.1208E-09	9.8349E-10	2.3342E-10
5	[illegible]386E-10		
	1.[illegible]572E-09		
	1.0325E-09	1.0512E-09	1.1948E-09
6	1.1662E-09		
	2.1041E-09		
	2.8712E-09	2.0472E-09	8.623E-10
7	3.2574E-10		
	4.1251E-10		
	4.5919E-10	3.9915E-10	1.2373E-09
8	3.4845E-10		
	4.1635E-10		
	4.8079E-10	4.152E-10	5.8339E-11
9	4.012E-10		
	3.861E-10		
	4.9813E-10		
	5.1192E-10	4.4934E-10	6.4845E-11
10	1.4433E-10		
	1.9969E-10		
	2.1198E-10		
	2.5182E-10	2.0195E-10	4.4397E-11

Exp.#	Individual BR^2	Average BR^2	Standard Deviation
11	1.2824E-10		
	1.7946E-10		
	2.5786E-10		
	2.5554E-10	21.0528E-10	6.2962E-11
12	3.2155E-10		
	4.466E-10		
	5.8343E-10	4.5052E-10	1.3098E-10
13	1.5759E-09		
	3.8705E-09		
	2.7185E-09		
	1.1584E-09		
	1.1197E-09	2.7216E-09	1.1473E-09
14	1.1584E-09		
	1.1197E-09		
	1.2256E-09	1.1676E-09	
15	1.72E-10		
	2.6082E-10		
	5.0254E-10	3.1179E-10	1.7106E-10
16	3.1862E-10		
	4.4281E-10		
	5.1057E-10		
	6.0133E-10	4.6833E-10	1.1908E-10
17	5.1752E-10		
	7.937E-10		
	6.8235E-10		
	6.5887E-10	6.6311E-10	1.1348E-10
18	2.367E-10		
	3.3783E-10		
	2.7761E-10	2.8405E-10	5.0872E-11

Table 2: BR^2 Values for Aluminia Oxide Particles in Corn Oil

Exp.#	Individual BR^2	Average BR^2	Standard Deviation
1	3.0635E-10		
	3.5871E-10		
	3.6324E-10	3.4276E-10	3.1622E-11
2	4.0585E-10		
	9.2209E-10		
	7.5492E-10	6.9429E-10	2.7139E-10
3	2.0106E-09		
	2.0358E-09		
	2.5053E-09		
	2.8399E-09	2.3479E-09	4.0393E-10
4	8.8345E-10		
	1.07E-09		
	1.2169E-09		
	1.7765E-09	1.2367E-09	3.8488E-10
5	2.0579E-09		
	2.5698E-09		
	2.7477E-09	2.4585E-09	3.5813E-10
6	4.5435E-10		
	7.6095E-10		
	1.1443E-09	8.5776#-10	3.1617E-10
7	6.5514E-10		
	1.2796E-09		
	1.2465E-09		
	1.7765E-09	1.2395E-09	2.969E-10
8	8.9246E-10		
	1.1117E-09		
	4.7899E-10		
	1.3821E-09	9.6632E-10	4.6352E-10
9	3.2635E-10		
	4.136E-10		
	4.7899E-10	4.0631E-10	7.6581E-11
10	4.06E-10		
	9.22E-10		
	2.51E-09		
	7.7812E-09	2.9036E-09	3.5914E-09

Appendix B:

Suspensions Characteristics

FIGURE 2: A nonaqueous suspension between to parallel plates.

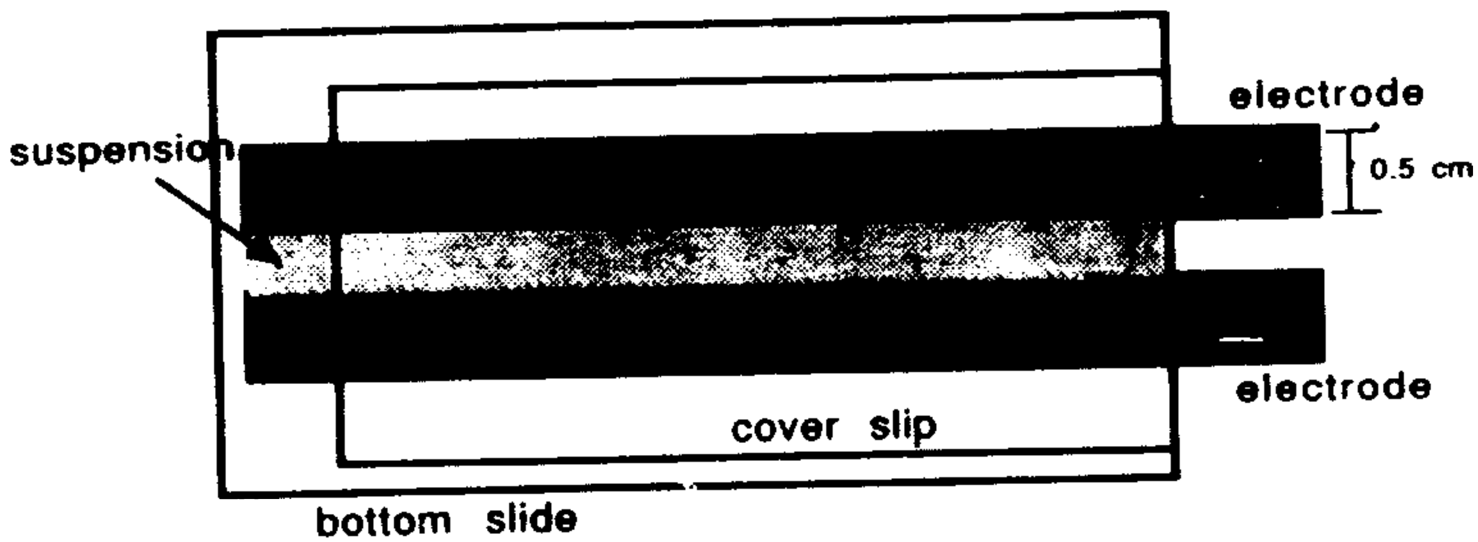


FIGURE 3: A flow diagram of the experimental setup.

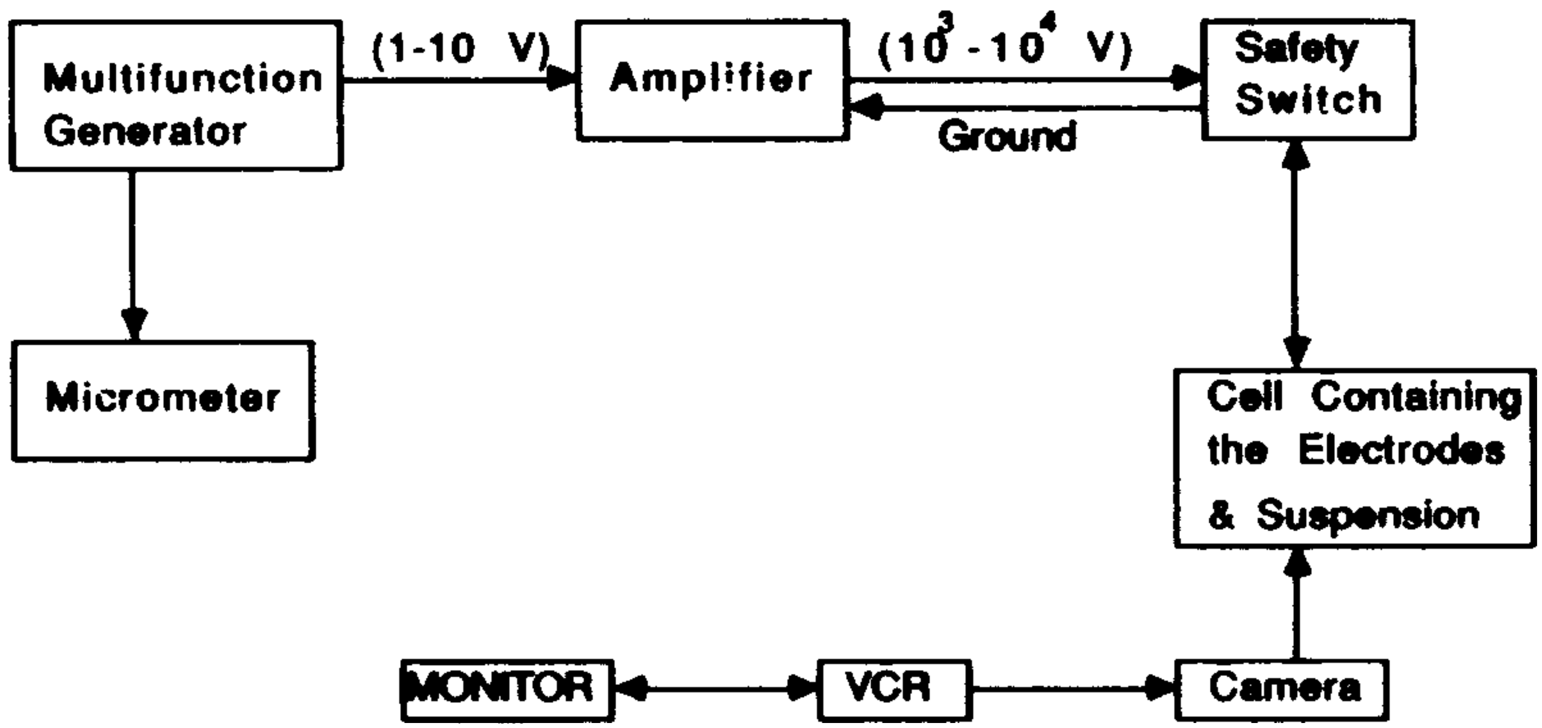


Table 3: Suspensions of Silica Particles.

EXP.#	Average Column Width $x10^{4}$ (m)	Average Distance Between Columns $x10^{4}$ (m)	Area Fraction
1	2.04	3.12	.655
	3.10	4.61	.672
3	1.92	4.25	.452
5	1.99	3.87	.514
5	1.71	3.64	.469
6	1.22	2.63	.464
6	1.34	2.93	.458
7	1.43	3.06	.467
7	1.35	2.86	.579
8	1.15	3.00	.384
8	1.41	3.11	.453
9	1.08	1.97	.496
9	1.44	2.86	.503
9	1.47	2.83	.520
10	1.77	2.92	.606
15	1.44	2.90	.635
15	2.1	3.31	.496
16	2.41	3.46	.695
16	1.84	3.16	.581
17	2.93	3.52	.842
17	2.09	3.57	.659
20	3.06	4.91	.623

EXP.#	Average Column Width $x10^4$ (m)	Average Distance Between Columns $x10^4$ (m)	Area Fraction
20	1.69	2.99	.566
22	2.62	3.80	.689
22	2.43	3.68	.578
23	1.80	3.47	.517
23	2.01	3.45	.583
24	1.12	2.72	.412
24	.80	2.33	.343
25	1.18	2.96	.398
25	1.91	3.21	.396
26	1.13	2.63	.428
26	1.38	3.48	.396
31	2.04	3.19	.638
31	1.46	2.38	.611
33	1.18	3.11	.378
33	1.63	3.27	.292
34	1.25	2.64	.478
34	1.42	2.94	.467
35	1.18	2.45	.485
36	5.69	2.18	.261
37	1.61	3.13	.482
39	1.60	3.19	.502
39	1.51	2.89	.522
40	1.44	3.03	.474

EXP.#	Average Column Width $x10^{4}$ (m)	Average Distance Between Columns $x10^{4}$ (m)	Area Fraction
40	1.67	3.25	.522
41	1.21	2.36	.513
42	1.63	3.68	.442
42	1.28	3.18	.393
43	1.32	3.76	.351
43	1.34	2.99	.449
45	1.28	2.90	.442
47	8.59	1.66	.516
47	7.90	1.38	.594
49	.896	1.65	.482
49	.986	1.49	.457
49	1.04	1.98	.526
50	.781	2.79	.280
51	.896	1.65	.542
51	1.01	1.97	.514
52	.750	2.06	.364
52	.632	1.66	.381

STANDARD DEVIATION

EXP. #	ST.DEV(AVE. COLUMN WIDTH)	ST.DEV(AVE. DISTANCE BETWEEN COLUMNS)
1	8.00E-05 m	1.10E-4 m
3	7.00E-05	1.60E-04
5	1.50E-04	1.00E-04
6	7.00E-05	1.30E-04
15	1.40E-04	3.60E-04
16	1.60E-04	1.70E-04
20	3.00E-04	4.20E-04
22	9.00E-05	1.90E-04
24	4.20E-05	9.00E-05
26	4.30E-05	1.50E-04
31	1.60E-04	2.00E-04
34	6.00E-05	1.50E-04
39	7.00E-05	1.80E-04
41	4.00E-05	7.00E-05
43	7.00E-05	1.50E-04
47	3.00E-05	5.00E-04
51	3.00E-05	5.00E-05
AVERAGES:	9.53E-05	1.92E-04

Table 3B: Standard Deviations.

Raw Data

SS 1

OIL (M)	PARTICLES	OIL+PARTICLE	OIL	PARTICLES	OIL+PARTICLE
1.59E-04	2.38E-04	3.97E-04	2.38E-04	7.54E-04	9.93E-04
1.19E-04	1.59E-04	2.78E-04	1.59E-04	3.18E-04	4.76E-04
1.19E-04	1.59E-04	2.78E-04	1.19E-04	7.94E-05	1.99E-04
3.97E-05	7.94E-05	1.19E-04	7.94E-05	1.19E-04	1.99E-04
1.19E-04	1.99E-04	3.18E-04	1.59E-04	2.78E-04	4.37E-04
1.59E-04	3.18E-04	4.76E-04			
3.97E-05	2.78E-04	3.18E-04			
AVERAGES					
1.08E-04	1.96E-04	1.06E-04	1.51E-04	3.10E-04	4.61E-04

SS 3

OIL 3	PARTICLES 3	OIL+PART.
1.67E-04	2.38E-04	4.05E-04
3.97E-05	2.38E-04	2.78E-04
2.38E-04	1.19E-04	3.57E-04
1.59E-04	1.19E-04	2.78E-04
4.76E-04	1.59E-04	6.35E-04
3.18E-04	2.78E-04	5.96E-04
AVERAGE		
2.33E-04	1.92E-04	4.25E-04

SS 5

OIL 5	PARTICLES	OIL+PART.
1.99E-04	1.19E-04	3.18E-04
5.57E-05	3.98E-04	4.53E-04
2.39E-04	1.19E-04	3.58E-04
1.19E-04	3.98E-04	5.17E-04
1.59E-04	7.95E-05	2.39E-04
3.58E-04	7.95E-05	4.37E-04
AVERAGES		
1.88E-04	1.99E-04	3.87E-04

OIL 5	PARTICLES	OIL+PART.
1.99E-04	1.35E-04	3.34E-04
1.59E-04	1.59E-04	3.18E-04
7.95E-05	1.19E-04	1.99E-04
1.27E-04	1.59E-04	2.86E-04
3.18E-04	1.35E-04	4.53E-04
2.78E-04	3.18E-04	5.96E-04
1.93E-04	1.71E-04	3.64E-04

OIL 6	PARTICLES	OIL+PART.
3.97E-05	5.56E-05	9.53E-05
1.59E-04	1.19E-04	2.78E-04
1.83E-04	1.59E-05	1.99E-04
1.35E-04	2.54E-04	3.89E-04
1.19E-04	1.59E-04	2.78E-04
7.94E-05	1.27E-04	2.06E-04
2.30E-04	1.19E-04	3.49E-04
1.27E-04	7.15E-05	1.99E-04
3.97E-05	7.94E-05	1.19E-04
3.18E-04	2.38E-04	5.56E-04
1.19E-04	1.03E-04	2.22E-04
AVERAGES		
1.41E-04	1.22E-04	2.63E-04

SS 6

OIL 6	PARTICLES	OIL+PART.
1.19E-04	3.97E-05	1.59E-04
7.94E-05	3.97E-05	1.19E-04
7.94E-05	1.99E-04	2.78E-04
1.59E-04	5.56E-05	2.14E-04
2.38E-04	1.99E-04	4.37E-04
1.59E-04	2.38E-04	3.97E-04
1.99E-04	2.38E-04	4.37E-04
1.59E-04	7.94E-05	2.38E-04
2.38E-04	1.19E-04	3.57E-04
1.59E-04	1.34E-04	2.93E-04

SS 7

OIL 7	PARTILCES	OIL+PART.
7.94E-05	1.19E-04	1.99E-04
1.99E-04	1.19E-04	3.18E-04
1.35E-04	2.38E-05	1.59E-04
1.75E-04	7.94E-05	2.54E-04
2.38E-04	1.99E-04	4.37E-04
1.59E-04	1.59E-04	3.18E-04
1.59E-04	1.27E-04	2.86E-04
1.59E-04	3.18E-04	4.76E-04
AVERAGE:		
1.63E-04	1.43E-04	3.06E-04

OIL 7	PARTICLES	OIL+PART.
1.59E-04	2.06E-04	3.65E-04
1.03E-04	3.97E-05	1.43E-04
7.94E-05	7.94E-05	1.59E-04
2.54E-04	2.38E-05	2.78E-04
2.94E-04	2.38E-04	5.32E-04
2.38E-04	2.14E-04	4.53E-04
7.94E-05	3.97E-05	1.19E-04
1.19E-04	1.59E-04	2.78E-04
1.19E-04	1.19E-04	2.38E-04
9.53E-05	1.83E-04	2.78E-04
1.19E-04	1.83E-04	3.02E-04
1.51E-04	1.35E-04	2.86E-04

SS 8

OIL 8	PARTILCES	OIL+PART.
2.30E-04	7.94E-05	3.10E-04
3.18E-04	2.38E-04	5.56E-04
2.86E-04	7.94E-05	3.65E-04
9.53E-05	3.97E-05	1.35E-04
1.99E-04	2.38E-05	2.22E-04
2.70E-04	3.97E-05	3.10E-04
1.27E-04	2.86E-04	4.13E-04
7.94E-05	1.59E-05	9.53E-05
4.76E-05	1.11E-04	1.59E-04
1.99E-04	2.38E-04	4.37E-04
AVERAGE:		
1.85E-04	1.15E-04	3.00E-04

OIL 8	PARTICLES	OIL+PART.
1.19E-04	7.94E-05	1.99E-04
9.53E-05	3.97E-04	4.92E-04
5.56E-05	5.56E-05	1.11E-04
9.53E-05	7.94E-05	1.75E-04
1.59E-04	7.94E-05	2.38E-04
1.99E-04	9.53E-05	2.94E-04
5.96E-04	9.53E-05	6.91E-04
1.35E-04	3.18E-04	4.53E-04
7.94E-05	7.15E-05	1.51E-04
1.70E-04	1.41E-04	3.11E-04

SS 9

OIL 9	PARTICLES	OIL+PART.
1.19E-04	7.94E-05	1.99E-04
1.59E-05	1.51E-04	1.67E-04
2.38E-04	3.18E-05	2.70E-04
7.94E-05	5.56E-05	1.35E-04
3.97E-05	7.94E-05	1.19E-04
3.97E-05	3.97E-05	7.94E-05
3.97E-05	2.38E-04	2.78E-04
7.94E-05	3.18E-05	1.11E-04
1.19E-04	1.19E-04	2.38E-04
1.59E-04	1.19E-04	2.78E-04
5.56E-05	2.38E-04	2.94E-04
AVERAGES:		
8.95E-05	1.08E-04	1.97E-04

OIL 9	PARTICLES	OIL+PART.
2.38E-04	1.19E-04	3.57E-04
1.03E-04	7.94E-05	1.83E-04
2.54E-04	3.73E-04	6.27E-04
1.35E-04	3.97E-05	1.75E-04
1.83E-04	3.97E-05	2.22E-04
1.59E-04	7.15E-05	2.30E-04
3.18E-05	1.19E-04	1.51E-04
7.94E-05	2.38E-04	3.18E-04
1.59E-04	1.59E-04	3.18E-04
7.94E-05	1.99E-04	2.78E-04
1.42E-04	1.44E-04	2.86E-04

SS 10

OIL 10	PARTICLES	OIL+PART.
1.27E-04	2.30E-04	3.57E-04
1.51E-04	1.19E-04	2.70E-04
3.97E-05	7.15E-05	1.11E-04
7.94E-05	2.94E-04	3.73E-04
1.51E-04	8.73E-05	2.38E-04
1.43E-04	2.62E-04	4.05E-04
AVERAGES:		
1.15E-04	1.77E-04	2.92E-04

SS 15

OIL 15	PARTICLES	OIL+PART.
5.56E-05	7.94E-05	1.35E-04
5.56E-05	1.83E-04	2.38E-04
1.27E-04	3.97E-05	1.67E-04
1.11E-04	2.30E-04	3.41E-04
1.75E-04	2.38E-05	1.99E-04
9.53E-05	7.15E-05	1.67E-04
4.76E-05	3.97E-05	8.73E-05
7.94E-05	2.38E-04	3.18E-04
7.94E-05	3.97E-05	1.19E-04
6.35E-04	4.92E-04	1.13E-03
AVERAGES		
1.46E-04	1.44E-04	2.90E-04

OIL 15	PARTICLES	OIL+PART.
2.38E-04	2.54E-04	4.92E-04
3.97E-05	2.38E-04	2.78E-04
1.59E-04	3.18E-04	4.76E-04
9.53E-05	1.27E-04	2.22E-04
7.15E-05	2.14E-04	2.86E-04
1.59E-04	6.35E-05	2.22E-04
1.59E-05	2.54E-04	2.70E-04
3.02E-04	2.62E-04	5.64E-04
6.35E-05	1.35E-04	1.99E-04
6.35E-05	2.38E-04	3.02E-04
1.21E-04	2.10E-04	3.31E-04

SS 16

OIL 16	PARTICLES	OIL+PART.		OIL 16	PARTICLES	OIL+PART.
1.35E-04	4.61E-04	5.96E-04		6.35E-05	2.86E-04	3.49E-04
1.27E-04	4.37E-04	5.64E-04		1.91E-04	1.19E-04	3.10E-04
6.35E-05	1.19E-04	1.83E-04		1.19E-04	3.18E-04	4.37E-04
1.59E-04	2.06E-04	3.65E-04		7.94E-05	1.75E-04	2.54E-04
7.94E-05	7.94E-05	1.59E-04		2.38E-04	7.94E-05	3.18E-04
1.03E-04	2.38E-04	3.41E-04		1.03E-04	1.27E-04	2.30E-04
7.94E-05	7.94E-05	1.59E-04				
6.35E-05	4.76E-04	5.40E-04				
1.19E-04	1.75E-04	2.94E-04				
1.27E-04	1.35E-04	2.62E-04				
1.06E-04	2.41E-04	3.46E-04	AVERAGES	1.32E-04	1.84E-04	3.16E-04

SS 17

OIL 17	PARTICLES	OIL+PART.
9.53E-05	3.33E-04	4.29E-04
9.53E-05	4.05E-04	5.00E-04
1.99E-04	1.43E-04	3.41E-04
1.27E-04	1.19E-04	2.46E-04
9.53E-05	3.33E-04	4.29E-04
1.19E-04	8.73E-05	2.06E-04
1.11E-04	1.59E-04	2.70E-04
7.94E-05	3.18E-04	3.97E-04
AVERAGES:		
1.15E-04	2.37E-04	3.52E-04

OIL 17	PARTICLES	OIL+PART.
4.76E-05	6.35E-05	1.11E-04
7.94E-05	3.97E-04	4.76E-04
3.65E-04	4.76E-04	8.42E-04
1.19E-04	3.57E-04	4.76E-04
5.56E-05	1.75E-04	2.30E-04
2.38E-05	1.67E-04	1.91E-04
1.59E-05	7.15E-05	8.73E-05
1.51E-04	2.94E-04	4.45E-04
1.35E-04	1.59E-05	1.51E-04
8.73E-05	7.15E-05	1.59E-04
1.08E-04	2.09E-04	3.57E-04

SS 18

OIL 18	PARTICLES	OIL+PART.		OIL 18	PARTICLES	OIL+PART.
1.43E-04	4.61E-04	6.03E-04		8.73E-05	1.27E-04	2.14E-04
4.76E-05	3.33E-04	3.81E-04		7.15E-05	3.89E-04	4.61E-04
1.19E-04	1.19E-04	2.38E-04		1.59E-04	9.53E-05	2.54E-04
7.15E-05	4.76E-05	1.19E-04		1.59E-05	1.19E-04	1.35E-04
1.19E-04	5.00E-04	6.19E-04		6.35E-05	3.97E-05	1.03E-04
2.46E-04	2.38E-04	4.84E-04		1.91E-04	3.65E-04	5.56E-04
6.35E-05	2.86E-04	3.49E-04		1.35E-04	1.67E-04	3.02E-04
				6.35E-05	1.51E-04	2.14E-04
				1.35E-04	4.37E-04	5.72E-04
				1.83E-04	1.59E-04	3.41E-04
				8.73E-05	9.53E-05	1.83E-04
1.16E-04	2.84E-04	3.99E-04	AVERAGES	1.08E-04	1.95E-04	3.03E-04

SS 20

OIL 20	PARTICLES	OIL+PART.		OIL 20	PARTICLES	OIL+PART.
1.19E-04	1.19E-04	2.38E-04		1.43E-04	6.35E-05	2.06E-04
9.53E-05	1.59E-04	2.54E-04		1.67E-04	3.97E-04	5.64E-04
7.94E-05	7.15E-05	1.51E-04		1.59E-04	9.53E-05	2.54E-04
1.27E-04	1.11E-04	2.38E-04		3.97E-05	3.18E-05	7.15E-05
1.91E-04	7.78E-04	9.69E-04		7.15E-05	1.03E-04	1.75E-04
5.00E-04	5.96E-04	1.10E-03		1.59E-04	3.33E-04	4.92E-04
				5.56E-05	6.35E-05	1.19E-04
				2.06E-04	1.19E-04	3.26E-04
				3.97E-05	4.45E-04	4.84E-04
				2.54E-04	3.97E-05	2.94E-04
1.85E-04	3.06E-04	4.91E-04	AVERAGES	1.29E-04	1.69E-04	2.99E-04

SS 22

OIL 22	PARTICLE	OIL+PART		OIL 22	PARTICLES	OIL+PART
1.91E-04	4.13E-04	6.03E-04		1.51E-04	3.33E-04	4.84E-04
2.14E-04	4.29E-04	6.43E-04		2.38E-04	2.30E-04	4.68E-04
9.53E-05	2.78E-04	3.73E-04		1.91E-04	3.41E-04	5.32E-04
6.35E-05	8.73E-05	1.51E-04		1.67E-04	3.26E-04	4.92E-04
9.53E-05	1.43E-04	2.38E-04		2.54E-04	1.51E-04	4.05E-04
9.53E-05	1.75E-04	2.70E-04		2.30E-04	1.83E-04	4.13E-04
1.03E-04	3.97E-04	5.00E-04		1.59E-05	1.35E-04	1.51E-04
8.73E-05	1.75E-04	2.62E-04				0.00E+00
1.18E-04	2.62E-04	3.80E-04	AVERAGES	1.78E-04	2.43E-04	3.68E-04

SS 23

OIL 23	PARTICLES	OIL+PART.		OIL 23	PARTICLES	OIL+PART.
1.03E-04	1.99E-04	3.02E-04		1.27E-04	3.26E-04	4.53E-04
2.94E-04	3.57E-04	6.51E-04		7.15E-05	8.73E-05	1.59E-04
1.03E-04	1.03E-04	2.06E-04		1.27E-04	1.67E-04	2.94E-04
1.51E-04	1.91E-04	3.41E-04		2.46E-04	1.27E-04	3.73E-04
5.56E-05	3.89E-04	4.45E-04		8.73E-05	1.35E-04	2.22E-04
1.19E-04	7.94E-06	1.27E-04		4.76E-05	6.75E-04	7.23E-04
1.11E-04	6.35E-05	1.75E-04		2.38E-04	6.35E-05	3.02E-04
4.05E-04	1.27E-04	5.32E-04		2.06E-04	3.18E-05	2.38E-04
1.68E-04	1.80E-04	3.47E-04	AVERAGES	1.44E-04	2.01E-04	3.45E-04

SS 24

OIL 24	PARTICLES	OIL+PART.		OIL 24	PARTICLES	OIL+PART.
8.73E-05	1.03E-04	1.91E-04		8.73E-05	9.53E-05	1.83E-04
2.70E-04	1.03E-04	3.73E-04		1.19E-04	8.73E-05	2.06E-04
1.91E-04	5.56E-05	2.46E-04		2.94E-04	5.56E-05	3.49E-04
1.51E-C4	7.15E-05	2.22E-04		3.65E-04	5.56E-05	4.21E-04
1.91E-04	8.73E-05	2.78E-04		1.51E-04	1.91E-04	3.41E-04
1.11E-04	1.59E-04	2.70E-04		7.15E-05	6.35E-05	1.35E-04
1.35E-04	1.67E-04	3.02E-04		8.73E-05	1.43E-04	2.30E-04
2.94E-04	1.67E-04	4.61E-04		4.76E-05	3.18E-05	7.94E-05
9.53E-05	1.35E-04	2.30E-04		2.30E-04	3.97E-05	2.70E-04
7.15E-05	7.15E-05	1.43E-04		3.97E-05	4.76E-05	8.73E-05
				6.35E-05	1.11E-04	1.75E-04
				1.91E-04	5.56E-05	2.46E-04
				2.46E-04	6.35E-05	3.10E-04
1.60E-04	1.12E-04	2.72E-C4	AVERAGES	1.53E-04	8.00E-05	2.33E-04

SS 25

OIL 25	PARTICLES	OIL+PART.		OIL 25	PARTICLES	OIL+PART.
1.91E-04	8.73E-05	2.78E-04		2.54E-04	1.43E-04	3.97E-04
3.26E-04	1.11E-04	4.37E-04		7.94E-05	3.18E-05	1.11E-04
2.06E-04	1.11E-04	3.18E-04		2.06E-04	1.75E-04	3.81E-04
4.76E-05	7.15E-05	1.19E-04		9.53E-05	3.81E-04	4.76E-04
8.73E-05	9.53E-05	1.83E-04		8.73E-05	3.81E-04	4.68E-04
1.11E-04	1.67E-04	2.78E-04		3.97E-05	8.73E-05	1.27E-04
8.73E-05	1.11E-04	1.99E-04		8.73E-05	1.35E-04	2.22E-04
1.11E-04	1.51E-04	2.62E-04				
3.02E-04	5.56E-05	3.57E-04				
9.53E-05	1.59E-04	2.54E-04				
3.97E-04	1.75E-04	5.72E-04				
1.78E-04	1.18E-04	2.96E-04	AVERAGES	1.21E-04	1.91E-04	3.12E-04

SS 26

OIL 26	PARTICLES	OIL+PART.		OIL 26	PARTICLES	OIL+PART.
4.13E-04	1.91E-04	6.03E-04		8.73E-05	3.26E-04	4.13E-04
2.38E-05	7.94E-05	1.03E-04		1.51E-04	1.03E-04	2.54E-04
4.76E-05	9.53E-05	1.43E-04		1.27E-04	5.56E-05	1.83E-04
3.10E-04	8.73E-05	3.97E-04		1.43E-04	1.59E-04	3.02E-04
9.53E-05	1.59E-04	2.54E-04		3.57E-04	1.27E-04	4.84E-04
7.15E-05	1.83E-04	2.54E-04		1.03E-04	1.83E-04	2.86E-04
1.75E-04	5.56E-05	2.30E-04		5.40E-04	1.19E-04	6.59E-04
7.94E-05	8.73E-05	1.67E-04		1.75E-04	3.18E-05	2.06E-04
1.27E-04	1.11E-04	2.38E-04				
3.97E-05	9.53E-05	1.35E-04				
2.78E-04	9.53E-05	3.73E-04				
1.51E-04	1.13E-04	2.63E-04	AVERAGES	2.10E-04	1.38E-04	3.48E-04

OIL 31	PARTICLES	OIL+PART.
1.19E-04	2.38E-05	1.43E-04
4.76E-05	9.53E-05	1.43E-04
1.19E-04	2.06E-04	3.26E-04
2.30E-04	7.15E-05	3.02E-04
3.97E-05	5.56E-05	9.53E-05
1.67E-04	3.33E-04	5.00E-04
3.18E-05	2.54E-04	2.86E-04
6.35E-05	2.78E-04	3.41E-04
2.22E-04	5.16E-04	7.38E-04
AVERAGES		
1.16E-04	2.04E-04	3.19E-04

SS 31

OIL 31	PARTICLES	OIL+PART.
9.53E-05	1.03E-04	1.99E-04
4.76E-05	2.06E-04	2.54E-04
1.11E-04	8.73E-05	1.99E-04
3.97E-05	7.15E-05	1.11E-04
1.99E-04	5.56E-05	2.54E-04
3.97E-05	1.11E-04	1.51E-04
7.15E-05	1.91E-04	2.62E-04
1.75E-04	3.81E-04	5.56E-04
1.75E-04	2.22E-04	3.97E-04
6.35E-05	1.03E-04	1.67E-04
6.35E-05	3.18E-05	9.53E-05
3.18E-05	1.83E-04	2.14E-04
9.26E-05	1.46E-04	2.38E-04

SS 33

OIL 33	PARTICLES	OIL+PART.
1.83E-04	9.53E-05	2.78E-04
1.27E-04	1.35E-04	2.62E-04
2.22E-04	1.27E-04	3.49E-04
9.53E-05	1.11E-04	2.06E-04
4.92E-04	1.27E-04	6.19E-04
1.03E-04	1.19E-04	2.22E-04
3.97E-04	5.56E-05	4.53E-04
1.03E-04	5.56E-05	1.59E-04
9.53E-05	2.38E-04	3.33E-04
1.19E-04	1.11E-04	2.30E-04
AVERAGE		
1.94E-04	1.18E-04	3.11E-04

OIL 33	PARTICLES	OIL+PART.
3.57E-04	3.18E-05	3.89E-04
3.73E-04	1.03E-04	4.76E-04
5.56E-05	5.56E-05	1.11E-04
1.51E-04	1.19E-04	2.70E-04
4.37E-04	1.75E-04	6.11E-04
7.15E-05	4.76E-05	1.19E-04
1.75E-04	1.35E-04	3.10E-04
2.31E-04	1.63E-04	3.27E-04

SS 34

OIL 34	PARTICLES	OIL+PART.
1.19E-04	1.19E-04	2.38E-04
4.76E-05	1.19E-04	1.67E-04
1.11E-04	8.73E-05	1.99E-04
6.35E-05	7.15E-05	1.35E-04
2.06E-04	2.46E-04	4.53E-04
1.99E-04	3.97E-05	2.38E-04
1.51E-04	1.83E-04	3.33E-04
2.46E-04	1.03E-04	3.49E-04
1.03E-04	1.59E-04	2.62E-04
AVERAGE		
1.39E-04	1.25E-04	2.64E-04

OIL 34	PARTICLES	OIL+PART.
1.67E-04	8.73E-05	2.54E-04
9.53E-05	1.19E-04	2.14E-04
3.18E-05	1.03E-04	1.35E-04
5.56E-05	2.30E-04	2.86E-04
3.26E-04	1.11E-04	4.37E-04
7.94E-05	1.75E-04	2.54E-04
1.35E-04	4.76E-05	1.83E-04
3.33E-04	2.06E-04	5.40E-04
1.43E-04	1.19E-04	2.62E-04
		0.00E+00
		0.00E+00
		0.00E+00
1.52E-04	1.42E-04	2.94E-04

SS 35,37

OIL 37	PARTICLES	OIL+PART.
1.03E-04	8.73E-05	1.91E-04
3.18E-05	6.35E-05	9.53E-05
2.14E-04	1.27E-04	3.41E-04
1.59E-04	3.57E-04	5.16E-04
1.51E-04	4.76E-05	1.99E-04
2.38E-05	5.56E-05	7.94E-05
8.73E-05	1.43E-04	2.30E-04
8.73E-05	1.59E-04	2.46E-04
1.75E-04	1.59E-04	3.33E-04
1.83E-04	7.15E-05	2.54E-04
1.91E-04	3.97E-05	2.30E-04
1.19E-04	1.11E-04	2.30E-04
1.27E-04	1.18E-04	2.45E-04

OIL 35	PARTICLES	OIL+PART.
1.75E-04	1.91E-04	3.65E-04
9.53E-05	5.56E-05	1.51E-04
1.51E-04	1.35E-04	2.86E-04
7.15E-05	6.35E-05	1.35E-04
1.91E-04	1.11E-04	3.02E-04
3.26E-04	2.22E 04	5.48E-04
7.94E-05	1.59E-04	2.38E-04
1.91E-04	1.91E-04	3.81E-04
1.75E-04	2.38E-04	4.13E-04
1.61E-04	1.52E-04	3.13E-04

SS 36

OIL 36	PARTICLES	OIL+PART.
1.91E-04	4.76E-05	2.38E-04
1.35E-04	2.38E-05	1.59E-04
7.15E-05	7.15E-05	1.43E-04
1.27E-04	6.35E-05	1.91E-04
2.06E-04	1.19E-04	3.26E-04
8.73E-05	1.59E-05	1.03E-04
9.53E-05	3.18E-05	1.27E-04
2.86E-04	9.53E-05	3.81E-04
3.10E-04	3.97E-05	3.49E-04
7.94E-05	6.35E-05	1.43E-04
2.94E-04	3.97E-05	3.33E-04
4.76E-05	7.15E-05	1.19E-04
1.61E-04	5.69E-05	2.18E-04

OIL 39	PARTICLES	OIL+PART.
2.38E-05	6.35E-05	8.73E-05
7.94E-05	1.35E-04	2.14E-04
4.13E-04	1.51E-04	5.64E-04
1.43E-04	1.51E-04	2.94E-04
2.22E-04	2.86E-04	5.08E-04
7.15E-05	1.75E-04	2.46E-04
AVERAGES:		
1.59E-04	1.60E-04	3.19E-04

SS 39

OIL 39	PARTICLES	OIL+PART.
8.73E-05	1.11E-04	1.99E-04
5.56E-05	1.91E-04	2.46E-04
1.03E-04	8.73E-05	1.91E-04
1.51E-04	5.56E-05	2.06E-04
1.83E-04	2.14E-04	3.97E-04
1.99E-04	1.67E-04	3.65E-04
1.91E-04	2.30E-04	4.21E-04
1.38E-04	1.51E-04	2.89E-04

SS 40

OIL 40	PARTICLES	OIL+PART.
9.53E-05	1.03E-04	1.99E-04
3.97E-05	1.83E-04	2.22E-04
3.41E-04	3.18E-05	3.73E-04
9.53E-05	1.03E-04	1.99E-04
1.35E-04	1.75E-04	3.10E-04
1.11E-04	2.70E-04	3.81E-04
1.59E-04	4.05E-04	5.64E-04
9.53E-05	5.56E-05	1.51E-04
7.94E-05	7.15E-05	1.51E-04
4.53E-04	1.03E-04	5.56E-04
1.51E-04	7.94E-05	2.30E-04
AVERAGES:		
1.60E-04	1.44E-04	3.03E-04

OIL 40	PARTICLES	OIL+PART.
9.53E-05	7.94E-05	1.75E-04
1.51E-04	2.54E-04	4.05E-04
1.03E-04	1.11E-04	2.14E-04
3.97E-04	2.22E-04	6.19E-04
3.65E-04	2.30E-04	5.96E-04
7.15E-05	4.76E-05	1.19E-04
2.38E-05	1.51E-04	1.75E-04
7.15E-05	4.37E-04	5.08E-04
1.59E-05	8.73E-05	1.03E-04
2.86E-04	4.76E-05	3.33E-04
1.58E-04	1.67E-04	3.25E-04

SS 41

OIL 41	PARTICLES	OIL+PART.
8.73E-05	9.53E-05	1.83E-04
6.35E-05	5.56E-05	1.19E-04
7.15E-05	1.67E-04	2.38E-04
1.11E-04	8.73E-05	1.99E-04
7.15E-05	1.35E-04	2.06E-04
2.62E-04	9.53E-05	3.57E-04
5.56E-05	2.14E-04	2.70E-04
1.35E-04	1.11E-04	2.46E-04
3.18E-05	1.59E-04	1.91E-04
2.38E-04	1.43E-04	3.81E-04
8.73E-05	1.27E-04	2.14E-04
[illegible]E-04	6.35E-05	2.30E-04

AVERAGES

1.15E-04	1.21E-04	2.36E-04

SS 42

OIL 42	PARTICLES	OIL+PART.
4.76E-05	4.76E-05	9.53E-05
6.35E-05	1.75E-04	2.38E-04
1.99E-04	1.51E-04	3.49E-04
3.41E-04	1.27E-04	4.68E-04
4.68E-04	2.54E-04	7.23E-04
2.30E-04	1.91E-04	4.21E-04
5.56E-05	3.10E-04	3.65E-04
2.38E-04	4.76E-05	2.86E-04
AVERAGES:		
2.05E-04	1.63E-04	3.68E-04

OIL 42	PARTICLES	OIL+PART.
5.56E-05	7.15E-05	1.27E-04
6.35E-05	1.43E-04	2.06E-04
1.43E-04	1.03E-04	2.46E-04
7.94E-05	3.97E-05	1.19E-04
3.10E-04	6.35E-05	3.73E-04
5.56E-05	9.53E-05	1.51E-04
4.37E-04	9.53E-05	5.32E-04
5.00E-04	3.10E-04	8.10E-04
9.53E-05	2.06E-04	3.02E-04
1.93E-04	1.25E-04	3.18E-04

SS 43

OIL 43	PATICLES	OIL+PART.
3.26E-04	1.83E-04	5.08E-04
1.91E-04	1.43E-04	3.33E-04
1.91E-04	1.27E-04	3.18E-04
4.45E-04	8.73E-05	5.32E-04
5.56E-05	6.35E-05	1.19E-04
4.37E-04	1.35E-04	5.72E-04
2.70E-04	3.97E-05	3.10E-04
3.97E-05	2.78E-04	3.18E-04
AVERAGES		
2.44E-04	1.32E-04	3.76E-04

OIL	PARTICLES	OIL+PART.
2.30E-04	2.14E-04	4.45E-04
2.46E-04	1.35E-04	3.81E-04
2.22E-04	1.75E-04	3.97E-04
1.51E-04	1.11E-04	2.62E-04
2.38E-05	5.56E-05	7.94E-05
8.73E-05	1.19E-04	2.06E-04
1.03E-04	1.51E-04	2.54E-04
1.19E-04	1.59E-04	2.78E-04
3.26E-04	2.38E-05	3.49E-04
1.35E-04	1.99E-04	3.33E-04
1.64E-04	1.34E-04	2.99E-04

SS 45

OIL	PARTICLES	OIL+PART.	OIL	PARTICLES	OIL+PART.
3.75E-05	3.75E-05	7.50E-05	4.38E-05	5.63E-05	1.00E-04
5.00E-05	1.38E-04	1.88E-04	5.00E-05	1.13E-04	1.63E-04
1.56E-04	1.19E-04	2.75E-04	1.13E-04	8.13E-05	1.94E-04
2.69E-04	1.00E-04	3.69E-04	6.25E-05	3.13E-05	9.38E-05
3.69E-04	2.00E-04	5.69E-04	2.44E-04	5.00E-05	2.94E-04
1.81E-04	1.50E-04	3.31E-04	4.38E-05	7.50E-05	1.19E-04
4.38E-05	2.44E-04	2.88E-04	3.94E-04	7.50E-05	4.69E-04
1.88E-04	3.75E-05	2.25E-04	3.81E-04	2.44E-04	6.25E-04
AVERAGES:					
1.62E-04	1.28E-04	2.90E-04	1.66E-04	9.06E-05	2.57E-04

SS 47

OIL 47	PARTICLES	OIL+PART.
1.00E-04	1.00E-04	2.00E-04
8.13E-05	6.88E-05	1.50E-04
1.88E-04	6.25E-05	2.50E-04
1.25E-05	5.63E-05	6.88E-05
6.88E-05	1.06E-04	1.75E-04
3.13E-05	1.50E-04	1.81E-04
6.25E-05	6.88E-05	1.31E-04
1.00E-04	7.50E-05	1.75E-04
AVERAGES		
8.05E-05	8.59E-05	1.66E-04

OIL 47	PARTICLES	OIL+PART.
1.13E-04	6.88E-05	1.81E-04
1.00E-04	6.25E-05	1.63E-04
1.88E-05	8.13E-05	1.00E-04
7.50E-05	1.06E-04	1.81E-04
3.13E-05	8.75E-05	1.19E-04
3.75E-05	1.00E-04	1.38E-04
8.75E-05	3.75E-05	1.25E-04
7.50E-05	9.38E-05	1.69E-04
3.75E-05	1.19E-04	1.56E-04
4.38E-05	8.75E-05	1.31E-04
2.50E-05	2.50E-05	5.00E-05
5.85E-05	7.90E-05	1.38E-04

SS 49

OIL 51	PARTICLES	OIL+PART
1.13E-04	1.44E-04	2.56E-04
3.75E-05	1.25E-04	1.63E-04
4.38E-05	1.00E-04	1.44E-04
1.06E-04	9.38E-05	2.00E-04
1.31E-04	6.88E-05	2.00E-04
1.19E-04	7.50E-05	1.94E-04
3.13E-05	7.50E-05	1.06E-04
2.50E-05	6.88E-05	9.38E-05
7.50E-05	5.63E-05	1.31E-04
AVERAGES:		
7.57E-05	8.96E-05	1.65E-04

OIL 51	PARTICLES	OIL+PART
5.63E-05	1.00E-04	1.56E-04
1.13E-04	3.75E-05	1.50E-04
3.75E-05	5.63E-05	9.38E-05
2.56E-04	1.19E-04	3.75E-04
1.63E-04	1.63E-04	3.25E-04
8.13E-05	1.06E-04	1.88E-04
8.75E-05	1.50E-04	2.38E-04
3.75E-05	2.50E-05	6.25E-05
3.13E-05	1.56E-04	1.88E-04
9.58E-05	9.86E-05	1.49E-04

SS 49,50

OIL 50	PARTICLES	OIL+PART.	OIL 49	PARTICLES	OIL+PART.
4.63E-04	8.75E-05	5.50E-04	2.06E-04	1.19E-04	3.25E-04
2.88E-04	1.25E-05	3.00E-04	8.13E-05	1.19E-04	2.00E-04
1.25E-04	1.31E-04	2.56E-04	1.25E-04	1.13E-04	2.38E-04
1.50E-04	5.63E-05	2.06E-04	7.50E-05	7.50E-05	1.50E-04
4.38E-05	4.38E-05	8.75E-05	6.25E-05	1.13E-04	1.75E-04
1.38E-04	1.38E-04	2.75E-04	1.25E-05	8.75E-05	1.00E-04
AVERAGES					
2.01E-04	7.81E-05	2.79E-04	9.38E-05	1.04E-04	1.98E-04

SS 51

OIL 51	PARTICLES	OIL+PART.	OIL 51	PARTICLES	OIL+PART.
1.13E-04	1.44E-04	2.56E-04	5.63E-05	1.00E-04	1.56E-04
3.75E-05	1.25E-04	1.63E-04	1.13E-04	3.75E-05	1.50E-04
4.38E-05	1.00E-04	1.44E-04	3.75E-05	5.63E-05	9.38E-05
1.06E-04	9.38E-05	2.00E-04	2.56E-04	1.19E-04	3.75E-04
1.31E-04	6.88E-05	2.00E-04	1.63E-04	1.63E-04	3.25E-04
1.19E-04	7.50E-05	1.94E-04	8.13E-05	1.06E-04	1.83E-04
3.13E-05	7.50E-05	1.06E-04	8.75E-05	1.50E-04	2.38E-04
2.50E-05	6.88E-05	9.38E-05	3.75E-05	2.50E-05	6.25E-05
7.50E-05	5.63E-05	1.31E-04	3.13E-05	1.56E-04	1.88E-04
7.57E-05	8.96E-05	1.65E-04	9.58E-05	1.01E-04	1.97E-04

SS 52

OIL 52	PARTICLES	OIL+PART.
1.69E-04	1.50E-04	3.19E-04
8.13E-05	1.06E-04	1.88E-04
1.88E-04	5.63E-05	2.44E-04
2.25E-04	5.00E-05	2.75E-04
5.63E-05	4.38E-05	1.00E-04
5.00E-05	4.38E-05	9.38E-05
1.50E-04	7.50E-05	2.25E-04
AVERAGES		
1.31E-04	7.50E-05	2.06E-04

OIL 52	PARTICLES	OIL+PART.
2.25E-04	7.50E-05	3.00E-04
1.06E-04	5.63E-05	1.63E-04
1.63E-04	8.75E-05	2.50E-04
4.38E-05	3.13E-05	7.50E-05
3.75E-05	5.63E-05	9.38E-05
5.00E-05	9.38E-05	1.44E-04
1.56E-04	6.88E-05	2.25E-04
7.50E-05	5.00E-05	1.25E-04
6.88E-05	5.00E-05	1.19E-04
1.03E-04	6.32E-05	1.66E-04