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DISPERSIVITY AS AN OIL RESERVOIR ROCK CHARACTERISTIC

FINAL REPORT
October 1, 1985 - September 30, 1988

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OBJECTIVES

The ultimate goal of this project is to establish dispersivity, α_d, as an oil reservoir rock property. The following investigations are being made at the University of Oklahoma as intermediary steps towards the final goal of this project:

1. To determine a standard technique for evaluating the dispersion characteristics of an oil reservoir rock.

2. To establish a correlation of dispersivity, α_d, with other core characteristics.

3. To evaluate the impact of physical properties of miscible and immiscible fluids on the dispersion characteristics of reservoir rocks.

4. To investigate a relationship between the dispersivity, α_d, of a reservoir rock and its relative permeability and capillary pressure curves.

5. To evaluate the effect of dispersivity, α_d, on the sweep efficiency of an EOR Flood.

PERSONNEL INVOLVED

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PREFACE

Several fundamental concepts about dispersivity and dispersion phenomena in reservoir rocks have been clarified during the term of this research project. Also, the concept of dispersivity as an oil reservoir rock characteristic has been investigated. The changes in dispersion phenomena in reservoir rocks in the presence of connate water have also been investigated in this study. A composite description with tabulated and illustrated results and correlations obtained in this study are presented in this report.

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Post Graduate:	Mark J. Warner, M.S.; S. N. Nwosu, Ph.D.; and Nadeem Malik, M.S.
Graduate :	Reza Shadizadeh, Ph.D. student; Saba Tahmassebi, Ph.D. student; and Yan Li, Ph.D. student.
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ABSTRACT

The main objective of this research project is to establish dispersivity, α_d, as an oil reservoir rock characteristic and to use this reservoir rock property to enhance crude oil recovery. A second objective is to compare the dispersion coefficient and the dispersivity of various reservoir rocks with other rock characteristics such as: porosity, permeability, capillary pressure, and relative permeability. The dispersivity of a rock was identified by measuring the physical mixing of two miscible fluids, one displacing the other in a porous medium.

A core was 100% saturated initially with a liquid oil product (resident fluid) which was then displaced by injecting a miscible liquid (displacing fluid). Samples of fluid produced from the outlet end of the core were analyzed for determining the percentage of the resident and the displacing fluid at the producing end. The extent of the spread of the concentration front (physical mixing) was measured from these samples by the use of a refractometer after calibration with the specific fluids. The miscible liquids consisted of crude oil, naphtha and various other mixtures of oil products. Mixtures of miscible liquids were used mainly to obtain equal viscosity, equal density fluids.

Several physical and flow characteristics were measured on the same core in order to investigate the correlation with dispersivity and dispersion coefficient.

A standard technique for measuring the dispersion coefficient, K, and the dispersivity, α_d, of an oil reservoir rock has been proposed. While conducting this research, a new low-cost, and rapid method of coating cores for laboratory flow studies has been developed.

Dispersion coefficients and dispersivities for several Berea sandstone cores were determined and attempts were made to correlate with other standard oil reservoir rock characteristics. A correlation was developed to correct for the difference in the viscosities of the two miscible fluids. A new method of calculating the "pseudo relative permeability" ratio of a miscible system was also proposed. A relationship between the average grain size of reservoir rocks and their corresponding dispersivities has been investigated.

Dispersion tests have been conducted on cores from a producing oil well, and an alternative method has been developed for testing the cores by cutting several plug samples from each core. The correlations developed so far between dispersivity and other core characteristics were verified and modified in some cases. A relationship between dispersivity, α_d, of a reservoir rock and its relative permeability and capillary pressure characteristics was also investigated. The authors introduced an original measure of the dispersivity variation for the test well.

These values have been compared to the values of the permeability variation and dispersion coefficient variation.

1.0 SUMMARY OF THE THREE-YEAR (1985-1988) STUDY

1.1 Introduction

The transport of solvent particles in porous media is influenced by diffusion and dispersion, which cause a mixing of the solvent over an increasing region. As flow continues the length of the transition concentration zone increases. The solvent spreading called mechanical dispersion is in the direction of flow and also normal to it. This spreading in a reservoir formation is also called hydrodynamic dispersion, and is thought to be a non-steady, irreversible process. The solvent concentration is measured at the end of an oil field core as a function of time or volume injected and is noted as a breakthrough curve. The hydrodynamic dispersion causes the breakthrough curve to be S-shaped.

At the microscopic level inside a pore there is a velocity variation in both magnitude and direction. There also exists a non-uniformity in the size and shape of the pores. Spreading of the solvent is caused by the variations of the flow and the pore system. The spreading is primarily in the longitudinal direction as compared to the transversal direction.

In this study molecular diffusion is neglected because of the short duration of the miscible displacements. There is also inhomogeneity on a macroscopic scale and permeability variations from one position to the next. We assume that in our experiments the solvent does not react with the solid surface of the formation, i.e., the effects of adsorption, deposition, solution of the solid, ion exchange, radioactive decay, and chemical reactions are negligible.

Matched density and viscosity (ideal tracer) experiments on the same length of core eliminate the dependence on the gravity and viscous forces.

In an isotropic porous medium the longitudinal dispersivity expresses the heterogeneity of the porous medium. It is related to tortuosity and permeability of the porous media and is characterized through Peclet number in unconsolidated packed beds. The transversal dispersivity is said to be approximately 15 times smaller than the longitudinal dispersivity for such a system.

In our consolidated rock experiments, spreading of the solvent is dominated by mechanical dispersion as long as Darcy's law holds. In our controlled laboratory experiments, the effects of molecular diffusion and transverse dispersion are negligible.

The entire theory of dispersivity can be extended to three phase flow (solvent, solute, water) where the oil phases fill only part of the pore space. We propose that the dispersivities then will be a function of the oil phase saturation.

The phenomenon of pore spaces in a consolidated reservoir rock that do not contribute to flow (dead end pores), appears to have an affect on the mechanical mixing and on the S-shape concentration curve. These pores are part of the effective porosity but have very small size, or very small pore throats.

1.2 Literature Review

Dispersion phenomena has been studied intensively for several decades and significant progress has been made. These studies have been conducted by many authors from many different fields such as chemical engineering, soil mechanics, geology, petroleum engineering, environmental engineering, and hydrogeology. Various branches of science and engineering have contributed vast amounts of literature, ranging from analytical and numerical to experimental, on development and application of dispersion theory. A brief synopsis of dispersion studies is presented in the following paragraphs.

Taylor (1953)[4] developed theories of dispersion for capillary tubes. Taylor assumed that the spreading of the mixing region resulted in parabolic velocity distribution in the capillary tube and that concentrations were equalized in a direction perpendicular to the flow by diffusion. Diffusion in the direction of flow was considered negligible in comparison to the convection. From his capillary tubes model, Taylor deduced that a dispersion coefficient is proportional to the second power of velocity.

Scheidegger (1954)[5] used a statistical approach to analyze dispersion in porous media. He indicated that the concentration distribution could be approximated by Gaussion distribution provided that dispersion follows Fickian behavior. The dispersion coefficient and dispersivity could then be calculated from the standard deviation of the normal distribution by the following equation:

$$\sigma = (2Kt)^{1/2} = (2\alpha_d x)^{1/2}$$

where
- σ = Absolute value of the standard deviation
- K = Dispersion coefficient
- t = Time
- α_d = Dispersivity
- x = Distance

Aris (1956)[6] extended Taylor's[4] analysis to straight tubes of any cross-section. He showed the dispersion coefficient to be linearly proportional to the mean velocity of flow. Aris' theory is in contrast with Taylor's work and the two are generally considered to represent the two extremes in dispersion theory.

deJong (1958)[10] used the Markov process which is equivalent to having a completely mixed cell. He showed that the dispersion coefficient is linearly related to the mean flow velocity.

Handy (1959)[14] conducted tests on a consolidated sandstone to study the effect of viscosity ratio and density differences between two miscible fluids. He concluded that the dispersion theory is applicable to all floods in which the viscosity ratio is either smaller or greater than one.

Bear (1960)[18] developed a one-dimensional dispersion model which consisted of an array of small cells with interconnecting short channels. In his analysis, he suggested that the dispersion phenomena is a combination of two processes; (1) complete mixing in the elementary cells, and (2) translation at the average flow velocity from one cell to the next through the connecting channels. He expressed the longitudinal dispersion coefficient, K_L by the following expression:

$$K_L = 1/2[(\Delta l')^2/\Delta l]\overline{U} = \alpha\overline{U}$$

Where $\Delta l'$ = Length of a mixing cell
Δl = Distance between centers of cells
$\overline{U}$ = Average flow velocity
α = Medium's longitudinal dispersivity

Scheidegger (1957, 1961)[8,24] formalized the general tensor form of dispersion coefficient for both isotropic and anisotropic homogeneous porous media. He summarized his analysis on the two possible relationships between dispersion coefficient (K) and mean flow velocity ($\overline{U}$) as follows: (1) $K \sim \alpha_g\overline{U}$, where α_g is a constant of the porous medium called geometric dispersivity applicable where there is no appreciable molecular transverse diffusion, and (2) $K \sim \alpha_{dyn}\overline{U}^2$, where, α_{dyn} is a constant of the porous medium called dynamic dispersivity and is derived by a dynamic procedure when there is appreciable mixing by molecular transverse diffusion.

Grane and Gardner (1961)[22] reported results of an experimental investigation of dispersion coefficient conducted on packings of glass spheres and a consolidated Berea sandstone core. They concluded that at low flow rates transverse and longitudinal dispersion are equal and are determined by the coefficient of molecular diffusion of the fluid and the formation factor of the porous medium. At high flow rates, transverse and longitudinal dispersion results from Berea sandstone core tests were shown to be proportional to the velocity of flow and independent of fluid properties.

Brigham, et al. (1961)[20] used the model of a bundle of capillary tubes and experimentally determined the dispersion coefficient in packs of granular material (beads and sands) and

consolidated Berea sandstone cores. They found the dispersion coefficient to be proportional to a power of the mean flow velocity. They concluded that the flow velocity exponent is dependent on the porous media and lies between 1.00 and 2.00.

Rumer (1962)[28] used quartz gravel and glass beads as a porous media for measuring the dispersion coefficient in steady and unsteady flow. He reported the dispersion coefficient to be proportional to flow velocity. For unsteady flow the proportionality was linear, for steady flow it was found to be non-linear. He expressed the relationship between longitudinal dispersion coefficient (K_L) and mean flow velocity ($\overline{U}$), as follows:

$$K_L = \alpha \overline{U}^n$$

Where, α and n are constants for a given medium. He discussed that both α and n are functions of the geometry of the pore system and they vary with porosity for a given medium. He showed that for the quartz gravel, with uniformity coefficient of 1.26, $\alpha = 0.2$ and $n = 1.083$ and for glass beads, with uniformity coefficient of 1.13, $\alpha = 0.027$ and $n = 1.105$. He discussed that the factor α, which has units of centimeters when $n = 1$, could be thought of as an intrinsic dispersivity analogous to permeability. Both parameters, permeability and dispersivity, are functions of the porous media and are important descriptives of the medium in the darcy flow range. The dispersion coefficient in his study was correlated to the rate of energy dissipation for laminar flow in the porous media:

$$K_L = (\text{constant})\alpha(G)^{n/2}$$

Where K_L, α, and n are defined previously, and G is rate of energy dissipation per unit mass of liquid.

Koval (1963)[33] studied the effect of viscosity difference on longitudinal dispersion. He developed the K-factor method which was the effect of viscosity difference and channeling on the efficiency of unstable completely miscible displacements.

Harleman and Rumer (1963)[31] correlated the ratio of longitudinal and transverse dispersion coefficients with Reynolds number (based on the average grain diameter), by the following expression:

$$\frac{K_L}{K_T} = \gamma R^n$$

where K_L = Longitudinal dispersion coefficient
K_T = Transverse dispersion coefficient
R = Reynolds number

γ and n are constants and are functions of the media characteristics. They conducted dispersion tests on a column packed with plastic sphere for steady flow and found that γ = 18.3 and n = 0.5. They concluded that the ratio of longitudinal to transverse dispersion coefficients increases with increasing seepage velocity and is independent of distance.

Perkins and Johnston (1963)[34] presented a review of diffusion and dispersion in porous media. They extensively reviewed both longitudinal and transverse dispersion and the effects of viscosity difference, density difference, turbulent flow and heterogeneity on dispersion of miscible fluids in a porous media. Their systematic discussion covered dispersion in a single capillary tube, network of short capillaries, and finally experiments on rocks of granular material. They discussed the effects of different variables on dispersion, including particle size and shape, column diameter in the case of packed tubes, particle size distribution, heterogeneities in the medium in the case of consolidated cores, and the presence of an immobile phase. It was found that non-spherical particles in a pack show more dispersion than packs of spherical particles of the same size. The viscosity ratio is shown to have a significant effect on dispersion. When viscosity of the displacing fluid is higher than the resident fluid, it causes a decrease in the dispersion coefficient. The unequal density in miscible flow also influences dispersion due to gravity forces. The turbulent flow region has been reported in terms of the Reynolds number.

Coats and Smith (1964)[36] developed a capacitance dispersion model. The model includes the existence of stagnant dead pores that contribute to total volume but are not open to flow. These pores help to account for the asymmetry seen in a concentration profile (breakthrough curve). The model does not necessarily represent the physical phenomena. It has been mainly suggested to obtain a better fit for the laboratory data.

Shamir and Harleman (1967)[38] conducted a series of experiments on longitudinal dispersion in a medium consisting of layers of sand. The longitudinal dispersion coefficient for each layer was determined as follows:

$$\frac{K_L}{v} = 0.9 \left[\frac{\bar{U} d_{50}}{v} \right]^{1.2}$$

Where K_L is the longitudinal dispersion coefficient; v is the kinemetic viscosity; $\bar{U}$ is the average flow velocity; and d_{50} is the grain sand diameter with 50% uniformity coefficient.

Klotz and Moser (1974)[46] conducted about 2500 tests on columns packed with different sands by using tracer injection. They used the statistical model of Scheidegger[5,12] to calculate the dispersion coefficient. The results of their experiments

showed that the dispersion coefficient depends linearly on the velocity as long as the mixing effect is primarily due to dispersion. From the results of these tests, longitudinal dispersivity was correlated with both liquid and porous media properties (Table 1).

TABLE 1. Correlation of dispersivity with flow and aquifer parameters (After Klotz and Moser[46]).

Parameter	Correlation with α_d
Kinematic viscosity	$\uparrow$: α_d $\uparrow$
Temperature of water	$\uparrow$: α_d $\downarrow$
Porosity	$\uparrow$: α_d $\downarrow$
Effective grain size	$\uparrow$: α_d $\uparrow$
Deviation of grain shape from a sphere	$\uparrow$: α_d $\uparrow$
Roughness and angularity of grains	$\uparrow$: α_d $\uparrow$
Uniformity coefficient	$\uparrow$: α_d $\uparrow$

Brigham (1974)[45] developed a graphical method to calculate dispersion coefficient using data from miscible displacements in short laboratory cores. The breakthrough relative concentration, C/Co, was plotted versus $[(I - 1)/I^{1/2}]$ on linear probability paper (I is the pore volumes injected). If the data fit a straight line, then the use of the diffusion equation was validated, and the dispersion coefficient could be calculated from the slope of the line.

Baker (1977)[49] modified the theory of Coats and Smith[36] to predict solvent slug size requirements where longitudinal dispersion and capacitance effects are dominant factors. He predicted in his model that the solvent concentration profile will fit the symmetrical profile predicted by the simple dispersion model of Brigham[45].

Schwartz (1977)[50] investigated macroscopic dispersion in a uniform heterogeneous geological formation. A hypothetical porous media consisting of a low permeability inclusion within a higher permeability medium was generated by simulating a stochastic method. Dispersion coefficients were computed by measuring reference particles moving through the medium. Distribution of the reference particles was shown to approach normal distribution with an increase in the number of conductivity elements. He showed whenever the low conductivity inclusion was distributed uniformly, a unique dispersion coefficient could be obtained. He concluded that dispersivity is influenced by the hydraulic conductivity of the porous media.

Hunt (1978)[52] developed solutions for instantaneous, continuous, and steady state pollution point sources in uniform groundwater flow. He used the general convection-dispersion equation and the Dirac delta function for initial distribution of

solute concentration. Some time was required for a continuous source to be in place before steady state condition was reached.

Gelhar, et al. (1979)[56] have shown macro-dispersivity to be proportional to the variance of the hydraulic conductivity of the plane perpendicular to the direction of flow in a stratified aquifer. For a short flow time, the Fickian transport model has been shown invalid and there are significant departures from normal concentration distribution. The Fickian behavior becomes valid when a solute travels for a long time through a heterogeneous porous media.

Freeze and Cherry (1979)[55] presented a brief discussion of dispersion and its relevance to the contamination of ground water. The hydrodynamic dispersion was defined as a combination of diffusion and dispersion. The authors distinguished three types of mechanisms which were responsible for microscopic dispersion. These were (1) the velocity gradient present in each pore channel, (2) tortuosity and pore size difference along a given flow path, (3) fingering, and branching along each pore channel. The velocity gradient was indicated to be the dominant factor controlling longitudinal dispersion. They indicated that the calculated dispersivity values from laboratory data were not the actual insitu dispersivity of the given geological formation. The authors did state that dispersivity values from tests on small samples could represent some property of the medium.

Klotz, et al. (1980)[58] extended their laboratory work to a field study where the results of 4,000 tests were used. They reported the linear correlation of the dispersion coefficient with flow velocity is not valid below a certain discharge velocity.

Smith and Schwartz (1981)[63] investigated the role of hydraulic conductivity measurements in influencing uncertainties in transport prediction by stochastic analysis through a Monte Carlo technique. They showed that measurements of hydraulic conductivity do not lead to large reductions in the uncertainty in the velocity field because the hydraulic gradient itself is a random variable. One possible implication which can be drawn from this study is that emphasis should be placed on in-situ measurement of seepage velocity which can be used to reduce the uncertainties of solute transport models.

Wood (1981)[64] developed a method for determining values of dispersivity for large-scale regional aquifer system using the concept of hydrochemical facies. Using Na^+ concentration of water in a coastal-plain aquifer, a concentration contour map was obtained. Hypothetical flowlines were drawn on the concentration contour map and imaginary columns were created along the lines to obtain breakthrough curves for each contour line. The breakthrough curves were compared to theoretically developed curves to determine dispersivity.

Batu (1983)[68] developed analytical expressions for two dimensional, unsteady dispersion of miscible fluids with flow through a homogeneous and isotropic porous medium. General solutions for different cases were presented in which they required the knowledge of (1) seepage velocity, (2) the input source concentration function, and (3) the longitudinal and lateral dispersion coefficients.

Stalkup (1983)[71,72] reviewed in detail some factors that affect miscible displacements. Dispersion plays a major role in oil field miscible displacement. The theory of dispersion was derived for first contact miscible fluids of equal viscosity and density. He also discussed the microscopic and macroscopic factors affecting dispersion.

Giordano and Salter (1984)[77] used a compositional simulator to study the influence of dispersion and phase behavior on the stability of laboratory scale displacements with unfavorable mobility. They used numerous experimental results on core floods conducted with tert-butyl alcohol, isooctane, and brine. They showed that for a stable flood the transverse velocity was much less than the axial velocity and the transverse dispersions were the dominant mechanisms. In addition, when the mobility was unfavorable, decreasing the transverse dispersivity allowed fingering of the displacing fluids.

Peters, et al. (1984)[81] presented a dimensionless stability number for testing the stability of miscible displacements in porous media. In order to calculate the stability number, dispersion parameter, K*, given by:

$$K^* = 2\varphi K_T \sqrt{\pi K_L t_o}$$

is required. In this equation, φ is porosity, K_T is the transverse dispersion coefficient, K_L is the longitudinal dispersion coefficient, and t_o is the maximum initial time required to reach the maximum concentration gradient. Numerous experiments of unstable miscible displacements, using glycerin as the oil phase and distilled water as solvent, were conducted on rectangular packs of unconsolidated sand. The results showed that D* was related to the darcy velocity, U, by a power law model of the form:

$$K^* = 0.00511(U/\varphi)^{1.04637}$$

They concluded that spectral analyses of unstable displacements can be used to determine the dispersion coefficients.

Dutta (1984)[74] performed numerous miscible displacement tests on sand packs and Berea sandstone cores to obtain longitudinal dispersivity and showed that dispersivity plays an important role in hydrocarbon recovery at very low recovery rates. Also in enhanced oil recovery, a miscible flood was shown to be more efficient if the dispersivity of the rock was high.

The effect of dispersivity became less important when high recovery was due to other favorable conditions. He suggested further investigation of the dispersion phenomena to include the study of the effect of pore size distribution, capillary pressure, relative permeability, and heterogeneity on the dispersion coefficient of a core.

Guven, et al. (1984)[79] used a moment method to solve the governing advection-dispersion equation for a horizontal stratified aquifer with vertical variations of hydraulic conductivity. They mentioned that the longitudinal macro-dispersivity depended on various factors: (1) aquifer thickness, (2) lateral dispersion coefficient; (3) average flow velocity, (4) mean travel distance of solute, and (5) hydraulic conductivity profile. The result of their study led to uncertainties in behavior of transverse dispersivity in natural stratified media. They suggested that reliable means of measuring field values of transverse dispersion coefficient and dispersivity were required.

Fattah and Hoopes (1985)[85] conducted laboratory tests on anisotropic and homogeneous porous media constructed for thin alternating layers of two types of sand. The hydraulic conductivity and longitudinal dispersion coefficient were found to be second rank tensors. The longitudinal dispersion coefficient had a linear relationship with the average flow velocity to a constant power 'n'. The exponent, n, is likely to be related to the flow direction.

Poulin (1985)[87] determined the linear dispersion coefficient, by miscible displacement tests performed on sandstones, using (1) a graphical method, (2) an analytical solution, and (3) a finite difference approximation method. The graphical method used was developed by Brigham (1974). This method was more sensitive to changes in flow rates. All three methods provided the same results. A certain relationship was detected between dispersion coefficient, flowrate, and porosity. But the extent of correlation was not developed.

Young (1986)[105] reported the feasibility of using physical dispersion relationships to account for the fluid mixing associated with viscous fingering. He proposed that the dispersivity was dependent upon viscosity gradient by this form:

$$\alpha_d = \alpha^* \exp(\beta(\partial \ln\mu/\partial x))$$

Where, α^* is the dispersivity for constant viscosity displacements; β is a constant; μ is the dynamic viscosity; and x is the direction of flow. Dispersivity calculated from the above equation gives a reasonable match with the experimental data. In addition, he developed a numerical method for simulating dispersion effects for systems with phase changes.

Lee and Okuyiga (1986)[96] in their statistical model of thin permeable porous media showed the dispersion coefficient to be proportional to the second power of the flow velocity.

Sahimi, et al. (1986)[101,102] used a Monte Carlo simulation of a continuous time, random walk model of the dispersion process in chaotic porous media. They showed the dispersion coefficient to be proportional to the velocity to the power 1.27.

Maini, et al. (1986)[97] studied the relationship between dispersion and wettability in miscible displacement. The dispersion coefficient was calculated in the dimensionless form using Brigham's method[45]. Their data mostly showed small deviation from a straight line, but in some cases where the deviation was more pronounced, more weight was given to the initial data. By using dimensionless dispersion coefficient for miscible displacement with residual oil and irreducible water, they obtained a simple quantitative index of wettability.

Menzie et al. (1988)[115] determined that the unsteady mixing of two miscible fluids displacing one another in a porous medium was governed by the dispersion phenomenon. In a microscopically disordered porous medium, two basic mechanisms drive the dispersion process. They rose from the chaotic nature of the pore level velocity field forced on the flowing fluid by the irregularity of the pore space (Sahimi[101,102]). In a disordered porous medium stream tubes become disrupted and continually break-up and rejoin at the junctions of flow passages. This leads to a wide variation in length of streamlines traversing the system, which is considered to be the kinematic mechanism of dispersion. As a result of changing pore geometry, orientation, and local pressure gradient of a streamline, the speed along the streamline varied considerably in traversing the medium. These two basic mechanisms caused a concentration front of fluid particles to spread as it advanced through the system. The extent of the spread of the concentration front of the fluid particles depended upon the dispersivity of the medium. This experimental study was designed to investigate the correlation of dispersivity with other reservoir rock characteristics.

1.3 Summary of Correlation of Dispersivity with Other Physical Characteristics of Rocks

The first step in this project was to establish a standard technique for measuring dispersivity, α_d, of an oil reservoir rock. Different techniques were tried both on sandpacks and core samples of reservoir rocks. A new core-mounting method, using liquid metal, was developed. This new method was also found to be simple, economic and safe. Cores mounted with this technique can also be safely used without leaks for high pressure displacements.

Two different techniques for measuring effluent concentrations were used- (i) using a conductivity meter, (ii) using a refractometer. More accurate and reliable results were obtained by the refractometer technique. Other techniques, such as distillation, tracers, and ion analyzer etc. were not used since they required different lab setups and the refractometric system yielded satisfactory results.

Koval's heterogeneity factor (H-factor)[33] for different experimental runs were determined. The H-factors were found to be higher for rocks with higher dispersivity. The method of determining the H-factor and the corresponding values for different experimental runs are shown in the latter part of this report.

The variation in pseudo permeability ratio of the resident fluid (oil) to the displacing fluid (naphtha), k_o/k_n, vs. saturation was determined by using a new technique. The pseudo permeability ratio decreased with decreasing saturation of the displaced fluid. This observation matches with the established pattern of change in relative permeability with saturation. Details of this pseudo permeability ratio determination from the experimental data of miscible dispersivity runs are shown in the latter part of this report.

An empirical equation for viscosity ratio correction has been developed for obtaining a standard dispersion coefficient. A standard dispersion coefficient (K_s) is defined as the dispersion coefficient obtained from a miscible flooding process with a viscosity ratio of the resident fluid to the displacing fluid as 1 ($\mu_r/\mu_d = 1$).

The dispersion coefficients, K, of reservoir rocks were found to increase with the total permeability, k, of the rock.

The Peclet number, Pe, has been determined for different experimental runs and correlated with the concentration profiles and washout functions. Theoretical variations of concentration profiles and washout functions with dimensionless time were also plotted and compared with the experimental profile. The theoretical and the experimental profiles match each other closely.

A brief description and illustrations of the laboratory observations and determinations thereof are furnished in the latter part of this report.

1.4 Accomplishments

The following major observations were made during the past three years of this study.

(a) A standard technique has been developed for measuring the dispersion coefficient, K, and the dispersivity, α_d, by using a refractometer, and a positive displacement pump.

(b) A new method of coating oilfield cores for laboratory studies has also been developed during this research work. It consists of applying a steel coating and aluminum wraps around the outer surface of a core.

(c) Koval's heterogeneity factor (H-factor)[33] for different experimental runs conducted recently were determined and found to increase in a scattered fashion for rocks with higher dispersivity. For different experimental runs the corresponding values of H-factors are shown in Table 6.

(d) The variation in pseudo relative permeability ratio of the displaced fluid to the displacing fluid with saturation changes of the displaced fluid was determined, using a new technique. The pseudo relative permeability variation for a miscible flooding system was thus obtained from the dispersivity runs.

(e) The experimental results (Figure 12) indicate that of all the relationships observed between the dispersion coefficient of a rock and its other physical properties, the most conspicuous relationship exists between the permeability and the dispersion coefficient.From the experimental results listed in Table 6, it may be noted that for the Berea sandstone cores, the dispersion coefficient, K, and the dispersivity, α_d, increased with the permeability, k, of the cores. This observation matches the findings of Dutta[74] and Harleman et al.[38] Recently, Patel et al.[111] have also reported that the dispersion coefficient increases with permeability. Miscible flooding experiments with Berea sandstone cores conducted in this study by displacing crude oil with naphtha showed a definite linear (on semilog) relationship between dispersion coefficient, K, (sq cm/sec) and permeability k (mD) of the cores. A plot of permeability against dispersion coefficient for different experimental runs is shown in the results section of this report. Also a generalized empirical equation governing the relationship between dispersion coefficient, K and permeability, k has been developed for a Berea sandstone core. The dispersion coefficient, K, and the dispersivity, α_d, were measured in the longitudinal direction of the sandstone cores in this study, and hence, can be more appropriately termed as longitudinal dispersion coefficient, K, and longitudinal dispersivity, α_d.

(f) An empirical equation for kinematic viscosity ratio correction has been developed for obtaining a standard dispersion coefficient. The densities of the resident and the displacing fluids are assumed to be equal ($\rho_r = \rho_d$) in the empirical equation. A standard dispersion coefficient (K_s) is defined as the dispersion coefficient obtained from a miscible flooding process with a kinematic viscosity ratio of the resident fluid to the displacing fluid as 1 (μ_r/μ_d=1).

(g) Experimental results were also obtained on several core samples during the past years to investigate the impact of the physical properties of the displacing and the displaced fluids on the dispersivity. The relative permeability, capillary pressure, Koval's heterogeneity factor, absolute permeability, porosity, and the grain size distribution data were measured on the same core samples. These rock properties were measured for each core sample and an attempt was made to correlate these properties with the respective dispersivity of the samples.

(h) With the introduction of brine (1% NaCl) as an initial wetting phase saturation, further effort was made to establish a standard technique for measuring dispersivity, α_d, of an oil reservoir in the presence of connate water saturation.

(i) Dispersion coefficients and dispersivities of several core samples were determined by using the standard technique developed in this research project. Experiments were conducted on the same core with and without immobile connate water saturations to study the effect of immiscibility.

(j) The Peclet number, Pe, has been determined for different experimental runs and correlated with the concentration profiles and washout functions. A theoretical variation of concentration profiles and washout functions with dimensionless time, $\bar{U}t/L$, were also plotted and compared with the experimental profile. The theoretical and the experimental profile match each other closely.

(k) Five capillary pressure runs have been conducted on five different Berea cores. Capillary pressure-saturation data was obtained on cores #3B, #5B, #6B, and #7B. The problem of early air breakthrough in the previous runs have been corrected. The capillary pressure curves for these cores and the relevant core data are shown in the latter part of this report.

(l) The pseudo relative permeabilities of the cores to the resident and the displacing fluid at different points of saturation during the displacement process were also calculated, using Johnson's method[15], from the experimental data obtained from the recent immiscible displacements. Water (1% NaCl) was introduced into core #6BW for the first time and displaced (Run #22) with an oil phase (ND8020 - 80% naphtha + 20% diesel oil) until no more water was observed in the effluent. Thus an immobile connate water saturation was left in the core for conducting a miscible displacement (run #23) of ND8020 by ISD8911 (isooctane 89% + diesel oil 11%). Pseudo relative permeability calculations have been made for run #22 and #23 from the displacement data. A plot of pseudo relative permeability vs. saturation is shown in the latter part of this report.

The relative permeability curves obtained by Jones[54] based on Johnsons's method[15] matched closely with the curve obtained

in run #22 (Figure 13). The relative permeability measurement technique used in this study can also be considered as a modified Welge method [15] and the results obtained by Welge also matched with the results of this investigation. The variation in pseudo permeability ratio of the resident fluid (oil) to the displacing fluid (naphtha), k_o/k_n vs. saturation was determined for miscible displacements by using a new technique. The pseudo permeability ratio decreased with decreasing saturation of the displaced fluid. The permeabilities of the cores to the resident and the displacing fluids at different points of saturation during the displacement process were calculated from the experimental data and the permeabilities were plotted against saturation. These observations match the established trend of immiscible relative permeability changes with saturation.

(m) The average grain size diameter of different Berea sandstone cores was measured by conducting sieve analysis and was correlated with the dispersivities of the cores. A plot showing the variation of dispersivity with the average grain size is shown in the latter part of this report.

2.0 EXPERIMENTAL METHOD FOR DETERMINATION OF DISPERSIVITY

A series of experimental runs were made on Berea sandstone, Saint Peter sandstone, unconsolidated sandpacks, and plug samples from oilfield cores for this study. The rock samples had different porosities, permeabilities and other characteristics.

2.1 Experimental Setup:

A schematic diagram of the experimental setup is shown in Figure 1. From a block of Berea sandstone, 2" diameter cores were drilled by using a coring bit. The cores were then dried in an oven for 48 hours at a temperature of 230°F. The Berea cores were coated with epoxy coating in the conventional manner at the very beginning of this study for conducting the runs, but were found to be vulnerable to severe damage and leakage at pressures higher than 30 psig. Moreover, channeling of fluid through the coating and sandstone interface was evident. Also, penetration of epoxy into the core sample was another matter of concern.

A new core mounting technique developed during this experimental study to overcome the aforementioned problems involved coating a core with liquid weld, (which is commercially available as J-B Weld), and heavy duty aluminum foil. A coating of liquid weld was first applied on the core and then a coating of heavy duty aluminum foil was applied. The same coatings were repeated twice in the same sequence and the core was mildly heated for early solidification of the liquid weld. The core was uniformly rotated while being heated for 2 hours and left for 24 hours for complete solidification of the coating. Three pressure-holding clamps were also used on the core for safety and better manageability of the core assembly.

The liquid-metal-coated core was then held at the ends by two aluminum end-plates. Two rubber gaskets were placed between the end plates and the core surface in order to prevent any leakage from the sides. The core assembly was then tested under water for leakage up to 90 psig by injecting air from one end into the core. When no leak was observed the core assembly was considered ready for experimentation. However, before beginning the actual experimental run the core was again oven-dried for 48 hours and the dry weight of the assembly was first recorded at the outset of the experimental run.

The complete experimental setup used for the miscible flooding process consisted of a high pressure, variable volumetric rate, positive displacement pump, graduated cylinders, 1/8" stainless steel tubing, pressure gauge, and a wet test meter (flowmeter).

The capillary pressure-saturation data were obtained from experimental runs on cores #3B through #7B. The capillary pressure runs were conducted inside an isothermal box made especially for this project. The experimental setup for a capillary pressure run is shown in Figure 2.

Early in the laboratory research work the linear coefficients of dispersion were calculated using the three methods proposed by Poulin[87]:

1. a graphical solution (Brighman's Method)[45]
2. an analytical solution of the diffusion equation
3. a finite difference solution of the diffusion equation

The experimentally obtained data from the laboratory runs were compared to the solutions by the three methods. The graphical solutions appeared to be the better method and this method was selected as the standard technique. The graphical method assumes the diffusion equation with consistent boundary conditions will produce a breakthrough curve plotted as a straight line. If the data plots as a curve, a model is required that includes a part of the pore space that does not contribute to flow.

In order to evaluate the reproducibility of the data by the proposed standard method of measuring dispersion coefficient and dispersivity, identical runs were conducted on core 9B. The results of the three repeat runs are shown in Figures 3, 4, 5 and 6 as runs 3, 4, and 5. The curves for the identical three runs are shown to produce a single average curve at each end of the concentration curve but a maximum deviation at the point of greatest concentration gradient. The reproducibility of the laboratory data by the proposed standard method appears to be satisfactory.

2.2 Theory and Procedure

The porosity and permeability of the core was first determined. Air was injected through the core and the flow rate at the outlet was measured by a wet test meter at a certain stable inlet pressure. Similarly, at different inlet pressures these values were recorded and the corresponding permeabilities were calculated by the equation:

$$k = 2q\mu L(P_2)/A\ [P_1 - P_2] \qquad (1)$$

Where q = Flow rate in cc/sec at P2

μ = Dynamic viscosity in cp at 71°F

L = Length of the core, cm

P_2 = Outlet pressure in atm

P_1 = Inlet pressure in atm

A = Cross-sectional area in cm^2

k = Longitudinal Permeability of the core to air in Darcy

These permeability values were plotted on coordinate paper against $1/P_m$ where, $P_m = (P_1 + P_2)/2$. The line passing through these points was extrapolated to infinite pressure i.e., $1/P_m = 0$ to get the total permeability of the core. The permeabilities obtained for different cores are listed under experimental results in the latter part of this report. The total permeabilities of the cores were also checked after initial 100% naphtha saturation by flowing naphtha through the cores and determining their liquid permeabilities.

The pore volumes of the cores were determined by saturating the cores completely with naphtha and weighing the cores to get the weight of naphtha in the void volumes, which, when divided by the specific gravity of naphtha yields the pore volumes of the cores. From the pore volumes and bulk volumes, the effective porosities of the cores were determined.

After the determination of porosities and permeabilities, the cores were again cleaned by injecting air and drawing a vacuum on the outlet end of the cores. The cleaning process was continued until it matched the dry weight of the cores. The cores were then dried in the oven again and saturated completely with crude oil in runs #4, #5, and #7 for displacement with naphtha. In runs #6, and #15 to 18 a mixture of isooctane (96.75%) and vegetable oil (3.25%), termed as Isoveg, was used to saturate the core and was displaced with a mixture of 90% naphtha and 10% crude oil, termed as NC9010. In runs #19 to 25 a mixture of naphtha(80%) and diesel oil(20%), termed as ND8020, was used

to saturate the core, which was then displaced by a mixture of isooctane (89%) and diesel oil (11%), termed as ISD8911. Since both the mixtures had the same viscosity, hence, either one of them could be used as the saturating or the displacing liquid. The viscosities of the resident and the displacing fluid were matched in runs #6 and #15 to 25.

During the miscible displacements, the effluent concentrations of the displacing fluid were determined by measuring the refractive index of the effluent mixture and obtaining the concentration values from the calibration curves prepared before the displacement runs. The displacing fluid continued to be injected until the effluent concentration of the displacing fluid reached 95% or more. The concentration profile against the pore volumes injected at different times during a typical experiment (run #25) is shown in Figure 7. Calculations and interpretations of data were performed by plotting the concentration profile versus pore volumes injected and parameter λ vs. effluent concentration of the displacing fluid.

The parameter λ is defined as[45]

$$\lambda = \frac{\frac{V}{V_p} - 1}{\sqrt{\frac{V}{V_p}}} \qquad (2)$$

where V = Effluent volume at any time during displacement in cc

Vp = Pore volume of core in cc

A plot of λ against concentration for run #25 is shown in Figure 8. From the resulting straight line of this Figure the values of $\lambda 90$ and $\lambda 10$ corresponding to 90% and 10% displacing liquid concentrations were read. The longitudinal dispersion coefficient, K, was then calculated from the following equation:

$$K = \frac{\bar{U}L\ (\lambda 90 - \lambda 10\ )^2}{(3.625)^2} \qquad (3)$$

Where L = Length of the core in cm
$\lambda 90$ = λ at 90% concentration of the displacing fluid
$\lambda 10$ = λ at 10% concentration of the displacing fluid
$\bar{U}$ = Average interstitial velocity in cm/sec = $\bar{q}/A$
$\bar{q}$ = Average injection flow rate in cc/sec

A = Cross-sectional area of the core in cm^2
ϕ = Effective porosity, fraction

Dispersivity, α_d, was then calculated by using the following equation :

$$\alpha_d = K/\overline{U} \tag{4}$$

where α_d = longitudinal dispersivity in cm
K = longitudinal dispersion coefficient in cm^2/sec.

This basic method for the determination of longitudinal dispersivity remained the same for runs 4 through 47. A sample calculation of dispersivity for run #25 is shown in the following page. It may be noted that the pore volume and porosity used in the calculation of this miscible displacement experiment was the hydrocarbon pore volume and porosity. The hydrocarbon pore volume was calculated by subtracting the connate water volume from the total pore volume of the clean dry core. The hydrocarbon porosity was calculated by dividing the hydrocarbon pore volume by the bulk volume of the core.

2.3 Sample Calculations

Calculation of Dispersivity
For Core # 4BW, Run #25

Length of the core, L	= 15.24 cm
Bulk volume, V	= 308.89 cc
Cross sectional area, A	= 20.268 cm^2
Run temperature, T	= 71°F
Total permeability of the core, k	= 8.5 mD
Hydrocarbon porosity, φ	= 10.76%
Hydrocarbon pore volume, Vp	= 14.95 cc
Displacing fluid (ISD8911)	= 89.00% isooctane + 11% diesel oil
Resident fluid (ND8020)	= 80% naphtha + 20% diesel oil
Average flow rate, $\bar{q}$	= 0.0097063 cc/sec
Average interstitial velocity, $\bar{U} = \bar{q}/A\varphi$	= 0.0097063/ (20.268 x 0.1076)
Or, $\bar{U}$	= 0.0045 cm/sec.

From Figure 8 $\lambda 90 = 0.54$ $\lambda 10 = -0.28$

Dispersion coefficient, K, is calculated by:

$$K = \frac{\bar{U}L(\lambda 90 - \lambda 10)^2}{(3.625)^2} = \frac{0.0045 \times 15.24 \times (0.82)^2}{(3.625)^2}$$

or $K = 0.0035\ cm^2/sec$

$$\text{Dispersivity, } \alpha_d = K/\bar{U} = \frac{0.0035}{0.0045}$$

or $\alpha_d = 0.7778$ cm

3.0 EXPERIMENTAL RESULTS

A series of experiments were performed in this study on each of the following different types of cores:

Group #1 - Berea sandstone cores (Length 6")
Group #2 - Saint Peter sandstone cores (Length 6")
Group #3 - Unconsolidated and consolidated sandpacks, (Length 9.5 - 125 ft.)
Group #4 - Plug samples from oilfield cores (Length 2").

The core samples in each of these groups had different porosities and permeabilities. Experimental data and the results obtained for each of the above different groups are summarized in Tables 2, 3, 4, 5, and 6 respectively. The effluent concentration profiles for runs 13, 14, 17, and 25 against pore volumes injected are shown in Figure 9. This graph of effluent concentration vs. pore volume injected is for a series of miscible displacements with different viscosity ratios (R_v). An empirical equation for viscosity ratio correction has been developed from this data. This equation

$$K_s = K[R_v]^n$$

can be used to obtain a standard dispersion coefficient (K_s).

Capillary pressure-saturation data were obtained from experimental runs on core #1B through #7B. The capillary pressure is given by the following equation:

$$P_c = P_{nw} - P_w$$

Where P_c = Capillary pressure, psi
P_{nw} = Pressure of non-wetting phase (air), psi
P_w = Pressure of wetting phase (oil), psi

Capillary pressure-saturation data were obtained for cores #3B, #5B, #6B and #7B. The curves showing the wetting phase saturations vs capillary pressures for cores #3B, #5B, #6B, and #7B and the relevant core data are shown in Figure 10. The semi-permeable membrane method of capillary pressure measurement was used to obtain this data (Figure 2).

4.0 DISCUSSIONS AND CORRELATIONS OF DISPERSIVITY

4.1 Correlation of Grain Size with Dispersivity

Sieve analyses of samples from the Berea sandstone blocks were conducted for determination of the representative values of the average grain diameter of various core samples. Results showing the variation in grain size with dispersivity and dispersion coefficient are listed in Table 7. Figure 11 shows the dispersivities of different Berea sandstones and their

corresponding grain diameter. The dispersivities of these core samples were determined by miscible displacement with the same effective viscosity ratio, Rv, of the resident and displacing fluid.

4.2 Permeability Correlation

The experimental results indicate that of all the relationships observed so far between the dispersion coefficient of a rock and its other physical properties, the most conspicuous relationship is found to exist between the permeability and the dispersion coefficient.

From the experimental results listed in Table 6, it may be noted that for the Berea sandstone cores the dispersion coefficient, K, increased with the permeability, k, of the cores. This observation matches the findings of Dutta[74] and Harleman et al.[38]. In a recent study Patel et al.[111] have also reported that the dispersion coefficient increases with the permeability. Miscible flooding experiments with Berea sandstone cores conducted by displacing crude oil with naphtha showed a definite linear relationship (with a semilog plot) between dispersion coefficient, K, (sq. cm/sec) and permeability k (mD) of the cores. A plot of permeability against standard dispersivity for different experimental runs is shown in Figure 12. A generalized equation governing this relationship can be written as:

$$K = a \log (k) + c \tag{5}$$

where K = Longitudinal dispersion coefficient, sq. cm/sec
k = Longitudinal permeability, mD
a,c = Constants

For Berea sandstone with naphtha displacing crude oil having a dynamic viscosity ratio (μ_o/μ_n) of 17.12 this empirical equation can be written as:

$$K = 0.01487 \log (k) - 0.012 \tag{6}$$

Similarly, values of these constants for different rocks and different viscosity ratios of the displaced and the displacing fluids can be determined.

The grain diameter, d_{gr}, can be expressed in Phi scale (Friedman, et al.[51]) is given by:

$$d_{gr} = - \log_2 (d/d_o)$$

where, d_o is a unit diameter of one millimeter and d is the average diameter of the sieve opening in millimeters in which the mineral grains are retained.

4.3 Pseudo-Relative Permeability Correlation

The relative permeabilities of the cores to the resident and the displacing fluid at different points of saturation during the immiscible displacement process were calculated, using Johnson's method [5], from the experimental data obtained from immiscible displacements. Water (1% NaCl) was introduced into core #6BW for the first time and displaced (run #22) with an oil phase (ND8020 - 80% naphtha + 20% diesel oil) until no more water was observed in the effluent. Thus an immobile connate water saturation was left in the core for conducting a miscible displacement (run #23) of ND8020 by ISD8911 (isooctane 89% + diesel oil 11%). Relative permeability calculations have been made for runs #22 and #23 from the displacement data. A plot of relative permeability vs. saturation for run #22 is shown in Figure 13 (immiscible drive).

The variation in pseudo permeability ratio of the resident fluid (oil) to the displacing fluid (naphtha), (k_o/k_n) vs. saturation was determined for a miscible displacement by using a similar technique and is plotted in Figure 14. The pseudo permeability ratio decreased with decreasing saturation of the displacing fluid. The permeabilities of the cores to the resident and the displacing fluid at different points of saturation during the displacement process were also calculated from the experimental data and the permeability profiles were plotted against saturation. These observations match the established trend of relative permeability changes with saturation for an immiscible system.

The variation in pseudo permeability ratio without connate water saturation of the resident fluid (oil) to the displacing fluid (naphtha), (k_o/k_n) vs. saturation was also determined for run #8. The pseudo permeability ratio without connate water saturation decreased with decreasing saturation of the displaced fluid. The pseudo permeabilities of the cores to the resident and the displacing fluid at different points of saturation during the miscible displacement process were also calculated from the experimental data and the permeability profiles were plotted against saturation as shown in Figure 15. These observations match the established trend of relative permeability changes with saturation.

4.4 Viscosity Correlation

To obtain a standard dispersion coefficient (K_s) a viscosity ratio correction factor was introduced. A standard dispersion coefficient (K_s) is defined as the dispersion coefficient obtained from a miscible flooding process when the displacing

fluid and the displaced fluid have the same viscosity and density.

During the experimental runs in a Berea sandstone core using different viscosity ratios of fluids, different dispersion coefficients were obtained. Experimental run #6 was conducted by using viscosity and density ratios of unity. From the results obtained the following empirical relationship was found to best match the values of dispersion coefficients.

$$K_s = K\left(\frac{\mu_r}{md}\right)^n \quad \text{for } R_v \geqslant 1 \tag{7}$$

where K_s = Standard dispersion coefficient, cm^2/sec at Rv=1
K = Dispersion coefficient at any given viscosity ratio, cm^2/sec
μ_r = Viscosity of the resident fluid, cp
μ_d = Viscosity of the displacing fluid, cp
R_v = (μ_r/μ_d) = Dynamic viscosity ratio
n = Empirical constant exponent

For the Berea core having a permeability of 90.0 mD, the value of the exponent 'n' was determined to be -0.71. The change in the value of this exponent, if any, with rocks of different permeabilities is under investigation.

Equation (5) can thus be written as:

$$K_s = K(\mu_r/\mu_d)^{-0.71} \tag{8}$$

Actual value of standard dispersion coefficient, K_s, for a Berea sandstone obtained with a viscosity ratio (Rv = 1) and the calculated values obtained by using equation (8) from different experimental runs are listed in Table 8.

If the dispersion coefficient is measured for a process with a viscosity density ratio of unity, one can calculate the dispersion coefficient of EOR processes with different viscosity ratios using equation (8).

4.5 Peclet Number Correlation

Peclet number is a dimensionless ratio of the product of average interstitial velocity and length divided by the dispersion coefficient. The following equation defines the Peclet number, Pe:

$$Pe = \frac{\overline{U}L}{K} \tag{9}$$

where $\bar{U}$ = Average interstitial velocity of the fluid mixtures during the miscible flood, cm/sec
L = Length of the core, cm (not length of pores)
K = Dispersion coefficient, sq. cm/sec

The dispersion coefficient, dispersivity, H-factor and Peclet numbers for the experimental runs #4-27 are listed in Table 6. Peclet numbers for different experimental runs are also shown in the following table:

PECLET NUMBERS FOR DIFFERENT RUNS

Run #	Pe
8	205.95
9	193.59
10	4.50
11	12.84
12	3.88
13	105.77
14	2.42
15	32.11
16	27.61
17	25.40
18	24.38
19	137.0
23	39.06
25	19.60
27	24.70

4.6 Dispersion Equation

The partial differential equation governing the dispersion phenomena is commonly expressed as:

$$K \frac{\partial^2 c}{\partial x^2} - \bar{U} \frac{\partial c}{\partial x} = \frac{\partial c}{\partial t} \tag{10}$$

where K = Dispersion coefficient, sq. cm/sec
c = Concentration, vol/vol
t = Time, sec
x = Distance in the flow direction, cm
$\bar{U}$ = Average interstitial velocity, cm/sec

The above equation can be written in a dimensionless form in terms of the Peclet number, $Pe = UL/K$, dimensionless time, $\tau = t\bar{U}/L$ and dimensionless distance, $X = x/L$, where L is the system length in cm:

$$\frac{1}{Pe}\frac{\partial^2 c}{\partial X^2} - \frac{\partial c}{\partial X} = \frac{\partial c}{\partial \tau} \tag{11}$$

A simplified solution of the above equation is given by[27,69]:

$$\frac{C}{C_o} = \frac{1}{2}\,\mathrm{erfc}\,\frac{(1-\tau)}{2\sqrt{\tau/Pe}} \tag{12}$$

If we define the washout function, W, as:

$$W = 1 - \frac{C}{Co}$$

then:

$$W = 1 - 1/2\ \mathrm{erfc}\,\frac{(1-\tau)}{2\sqrt{\tau/Pe}} \tag{13}$$

A plot of theoretical and experimental values of washout function, W vs. dimensionless time, τ for the Peclet numbers obtained for runs #6 and 7 are shown in Figures 16 and 17 respectively.

It may be noticed that for run #6 the theoretical curve closely matched the experimental profile (Figure 16) for the matched viscosity flood. The viscosity ratio of the displaced fluid (isooctane) to the displacing fluid (NC9010) was one in run #6.

The viscosity ratio of the displaced fluid (crude oil) to the displacing fluid (naphtha) was 17.12 in run #7. This is considered to be very high and unfavorable viscosity ratio. The deviation of the experimental values (Figure 17) from the theoretical values in this run may be attributed to the unfavorably high viscosity ratio. The hump observed in the experimental curve of Figure 17 just before the one PV injected is an indication of early breakthrough of viscous fingers. Since the viscosity ratio is high, the displacement front (or the mixed region) is unstable. This further justifies the necessity of using unit viscosity ratio displacements to eliminate the effect of viscous forces.

In order to compare the Dykstra Parsons permeability variation (Craig (1971)[42]), V_k, on a selected oil well with the dispersion coefficient and dispersivity variation on the same well, the plug cores were analyzed. The measured and calculated data are presented in Table 5. Permeability measurements on the plug cores are plotted on log-probability paper (Figure 18) to give a permeability variation (V_k=0.618) for this Red Fork sand well.

Assuming log normal dispersion coefficient and dispersivity distributions, we have introduced a measure of variability of these quantitites based on the Dykstra Parsons' proposed method[42]. Dispersion coefficients are plotted on log-probability paper. We define the dispersion coefficient variation, V_K, as:

$$V_K = \frac{\overline{K} - K\sigma}{K}$$

where; K = Dispersion coefficient value with 50 percent probability

$K\sigma$ = Dispersion coefficient at 84.1 percent of the cumulative sample

The dispersivity variation, V_{α_d}, is defined in the same manner:

$$V_{\alpha_d} = \frac{\overline{\alpha_d} - \alpha_d\sigma}{\alpha_d}$$

where; $\overline{\alpha_d}$ = Dispersivity value with 50 percent probability
$\alpha_d\sigma$ = Dispersivity at 84.1 percent of the cumulative sample.

The dispersion coefficients calculated from the miscible displacement experiments on the Red Fork plug cores gave a dispersion coefficient variation (V_K=0.419) and is shown on Figure 19. The same core plugs from this well produced a dispersivity variation V_{α_d} of 0.415 as shown in Figure 20. The measured and calculated data on these cores produce an acceptable straight line in each case. This suggests a single value of V_K and V_{α_d} to describe the variation of dispersion coefficient and dispersivity for this well.

4.7 Correlation of Data

Of all the parameters that enter into miscible transport calculations, the dispersion coefficient tends to be the most difficult to determine. Dispersion coefficient describes the spreading of miscible fluids as they migrate away from the injection well. It has been correlated with the product of the mean flow velocity and a characteristic mixing length called the hydrodynamic dispersivity. Dispersivity has been suggested to be a characteristic property of the porous media (rock), but it is not yet fully understood.

The experimental data of this research program used multiple regression analysis to represent the relationship between

dispersivity and known porous media properties; permeability, void ratio, porosity, etc.

The overall objective was to develop a linear regression model describing dispersivity of the porous media. Some of the more significant issues are listed below:

1. Is there any relationship between dispersivity and each individual porous media property?

2. Is there any linear relationship between dispersivity and flow velocity?

3. Can dispersivity be predicted by knowing the flow velocity?

4. Can dispersivity be used to predict miscible movement in an oil reservoir?

The results are of interest to a significant and growing number of petroleum engineers. Predicting the dispersivity value from rock properties would represent a significant advancement toward understanding subsurface miscible transport and EOR processes.

The data used in this project are shown in Table 9. The response and predictor variables are described as follows:

4.7.1 Response variable

The response (dependent) variable is dispersivity [y]. Dispersivity has been suggested to be a rock property that causes a solute concentration to spread as it moves through a porous medium.

4.7.2 Predictor variables

Predictor (independent) variables are the flow system properties. The predictors considered are:

a. Permeability, [x_1]
b. Porosity, [x_2]
c. Void ratio, [x_3]
d. Heterogeneity, [x_4]
e. Darcy velocity, [x_5]
f. Dispersion coefficient, [x_6]

These predictors were used since each of them represents a porous medium property except the dispersion coefficient which contains both fluid and porous medium properties. If the dispersivity has a linear relationship with these predictors, it will be proven that the dispersivity is in fact a rock property.

Table 10 shows the correlation matrix. The correlation matrix shows that there is medium and positive correlation between predictors x1, x2, and x3 and they have almost the same correlation value with the response variable y. As expected, there is high correlation between the response y and the predictor x6. The predictors x4 and x5 have the lowest correlation values compared to other variables.

Table 11 presents means, standard deviation, minimum and maximum values of the variables. Table 12 shows the data for box and whiskers plot of the variables. Figures 21 to 27 are box and whiskers plots of the variables. Plots of box and whiskers of the variables shows:

(1) The predictors; x1, x4, x5, and x6 are skewed to the right while x2 and x3 are skewed to the left.

(2) The response y, has high skewness which has the direction to the right.

(3) The predictor's medium, x1, x2, x3, and x5 are shifted toward the direction of the skewness.

Extensive statistical analysis of thirty-four miscible displacement runs indicates that there are no outliers.

The main objective of this study was to identify if dispersivity is a rock characteristic. Based on this statistical analysis the following remarks can be made:

1. Dispersivity is not only a rock property but it is a function of both fluid and porous media properties.

2. Neither permeability nor porosity alone can be used to predict the dispersivity.

3. In this study of miscible flooding, dispersivity can not be assumed to be a constant value. It may be changing with respect to the fluid movement in a porous medium.

It has been noted in the literature that dispersion is both a porous media and flow property. In this study, we have attempted to eliminate the flow dependence of the dispersion. In the miscible displacement experiments in consolidated porous media, matched viscosity and density fluids were used to nullify the viscous and gravity effects (i.e., viscous dissipation, fingering, gravity override, etc.). Flow experiments were conducted at flow rates low enough that Darcy law holds, therefore turbulence or non-Darcy behavior is eliminated.

Time elapsed between the srart and termination of the floods were brief, consequently molecular diffusion could be neglected. Experiments were carried out in absence of immobile saturations so that the flow system was equivalent to the one phase flow with

an effective permeability equal to the absolute permeability. All correlations made were with cores of the same size and the length to diameter ratio was large, this eliminated the effects of variable length and transverse dispersion.

All experiments were conducted and monitored under the controlled conditions mentioned. One would expect that since all flow effects have been eliminated, dispersion coefficients and dispersivities measured should solely be a function of the porous media. However, as it has been demonstrated in the report, this is not the case. Dispersion remains a poorly understood property of the rock and the flow system. The authors believe that dispersion in porous media is a complicated phenomena and there must be other flow properties involved in the displacement process affecting dispersion that are not presently considered.

After all the previous laboratory studies it still remains unresolved weather or not dispersion like permeability or porosity, could be regarded as an independent characteristic parameter in studies of flow of fluids in a porous media.

The findings of this investigation emphasize the need for more research on the dispersion of miscible fluids in porous media.

5.0 CONCLUSIONS

A standard technique for determining the dispersion coefficient and dispersivity has been developed in this study. By using the dispersion measurement techniques as described in this paper, the extent of unsteady mixing of a resident fluid with the injected fluid in an oil reservoir rock can be determined.

Dispersivities of several Berea sandstone cores were experimentally determined and attempts were made to correlate dispersivity and dispersion characteristics with other rock characteristics. A slight relationship of the dispersion characteristics was indicated to exist between the dispersion coefficient and the total permeability of a core.

A correlation has also been developed to correct the viscosity effect of the displacing and the displaced fluid on the dispersivity of a reservoir rock.

Average grain diameter of several Berea cores were determined by sieve analysis and correlated with the dispersion coefficients and dispersivities of the corresponding core samples. The dispersion coefficients and dispersivities of the berea sandstone cores were found to increase with the increasing grain size.

Koval's (1963) heterogeneity factor[33] for the Berea sandstone cores showed some particular trend of variation with the corresponding dispersivities and dispersion coefficients.

The advantages of using the dispersion characteristics of an oil reservoir rock over some of the other characteristics are summarized below:

(i) The absolute permeability of a rock often varies with the types of fluids injected, whereas the standard dispersion coefficient, K_s, of a core was found to be the same when different fluids were used to conduct the displacement experiments.

(ii) The experimental determination of dispersivity is much simpler and easier than the measurement of absolute permeability of a rock.

While pursuing a standard technique, a new method of coating the core samples for laboratory studies has been developed during this investigation.

Dispersivities of different lithologic zones of an actual oil well are being experimentally determined from the representative core samples obtained during the oil well drilling. Other physical characteristics are also being measured on the same core samples for investigating possible relationships with dispersivity.

6.0 NOMENCLATURE

A = Cross sectional area, cm^2
BV = Bulk volume, cc
c = Concentration, vol/vol
d = Average diameter of the sieve opening, mm
d_{gr} = Grain diameter, Phi scale
d_o = Unit diameter of one mm
dp = Particle diameter, cm
d_{50} = Grain diameter with 50% uniformity coefficient
G = Rate of energy dissipation per unit mass of liquid
H = Heterogeneity factor
I = Pore volumes injected, V/V_p
k = Permeability, mD
k_{ro} = Relative permeability of oil
k_{rw} = Relative permeability of water
K = Dispersion coefficient, cm^2/sec
K^* = Dispersion parameter, cm^3/sec
L = Length, cm
n = constant exponent
P = Pressure, atm
Pe = Peclet number
q = Volumetric flow rate, cc/sec
R = Reynolds number
R_v = Viscosity ratio
S = Saturation, vol/vol
t = Time, sec
t_o = Maximum time to reach the maximum concentration gradient
T = Temperature, ^oF
U = Interstitial velocity, cm/sec
V = Volume injected, cc
V_k = Permeability variation
V_K = Dispersion coefficient variation
V_{α_d} = Dispersivity variation
V_p = Pore volume, cc
W = Washout function
x = Distance, cm
x_1, x_2, x_3, x_4, x_5, x_6 = Predictor variables
X = Dimensionless distance
y = Response variable

Greek Letters:

α = Medium's longitudinal dispersivity, cm
α_d = Dispersivity, cm
α_{dyn} = Dynamic dispersivity
α_g = Geometric dispersivity
α^* = Dispersivity of constant viscosity displacements
γ = Media dependent constant
Δl = Distance between centers of wells
$\Delta l'$ = length of a mixing cell
φ = Porosity, fraction
λ = $[(V/V_p) - 1]/\sqrt{(V/V_p)}$
ρ = Density, gr/cc

τ = Dimensionless time
μ = Dynamic viscosity, cp
ν = Kinematic viscosity
σ = Standard deviation

Subscripts:

c = Capillary
d = Displacing
L = Longitudinal
n = Naphtha
nw = Non-wetting
o = Oil, initial
r = Resident
s = Standard
w = Water, wetting
wc = Connate water
1 = Inlet
2 = Outlet

$\bar{\ }$ = Average

7.0 RELATED PRESENTATIONS AND PUBLICATIONS

1. Dutta, S. and Menzie, D.E.: "Dispersivity as an Oil Reservoir Rock Characteristic", paper presented at Montana Tech. Butte, Montana (Sept. 1984)

2. Dutta, S. and Menzie, D.E.: "Dispersivity as an Oil Reservoir Rock Characteristic", paper presented at the National Institute for Petroleum and Energy Research, Bartlesville, Oklahoma (Aug. 1984)

3. Menzie, D.E., Dutta, S., and Shadizadeh, R.: "A New Metallic Method of coating Oilfield Core for Laboratory Studies", J. Pet. Tech. (May 1988) 643-644

4. Menzie, D.E., Dutta, S., Shadizadeh, R. and El-Ageli, M.A.: "Dispersivity as an Oil Reservoir Rock characteristic", presented in the Southwest Regional Meeting of Am. Chem. Soc., Houston, TX (Nov. 19-21, 1986)

5. Dutta, S., Menzie, D.E. and Shadizadeh, R.: "Identification of a new Rock Characteristic For Economic Selection of Disposal sites for Toxic/ Hazardous Waste", presented at the Fourth Ann. Meeting of the Am. Soc. for Surface Mining and Reclaimation, Billings, Montana (March 17-20, 1987)

6. Shadizadeh, R. and Warner, M.J.: "Experimental Determination of Dispersivity as a Reservoir Rock Characteristic for Groundwater Aquifer" presented at the Ann. Meeting of the Oklahoma Academy of Science, Tahlequah, Oklahoma (Nov. 14, 1986)

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TABLE 2. Experimental data and results obtained for Berea sandstone cores (Length 6").

Group #1

PARAMETER	RUN #4 (core #1B)	RUN #5 (core #2B)	RUN #6 (core #3B)	RUN #7 (Core #3B)	RUN #8 (Core #3B)
Type of Core	Berea Sandstone	Berea Sandstone	Berea Sandstone	Berea Sandstone	Berea Sandstone
Longitudinal dispersivity, α_d	6.17	1.45	0.37	3.3	0.072
Longitudinal dispersion coeff., K (cm^2/sec)	0.023	0.0055	0.0022	0.0165	0.00037
Porosity, ϕ (%)	22.60	22.60	18.10	18.10	18.10
Permeability, k (mD)	225.00	15.00	90.00	90.00	90.00
Core Length, L (cm)	13.97	13.97	15.24	15.24	15.24
Average interstitial velocity, $\bar{U}$ (cm/sec)	0.00373	0.00380	0.00595	0.0050	0.005
Pore Volume, V_p(cc)	64.05	64.05	56.00	56.00	56.05
Dynamic Viscosity ratio, R_v (μ_r/μ_d)	17.12	17.12	1.0	17.12	0.058
Immobile Water Saturation, Swc (%PV)	0.0	0.0	0.0	0.0	0.0

TABLE 2. Group #1 (continued)

PARAMETER	RUN #9 (core #4B)	RUN #10 (core #4B)	RUN #11 (core #5B)	RUN #12 (Core #5B)	RUN #13 (Core #6B)
Type of Core	Berea Sandstone	Berea Sandstone	Berea Sandstone	Berea Sandstone	Berea Sandstone
Longitudinal dispersivity, α_d	0.79	3.39	0.12	3.93	0.13
Longitudinal dispersion coeff., K (cm^2/sec)	0.00037	0.0167	0.00564	0.0196	0.0006
Porosity, ϕ (%)	19.60	19.60	19.80	19.80	22.80
Permeability, k (mD)	98.00	98.00	143.00	143.00	680.00
Core Length, L (cm)	15.24	15.24	15.24	15.24	15.24
Average interstitial velocity, $\bar{U}$, (cm/sec)	0.0047	0.00493	0.00475	0.005	0.0042
Pore Volume, V_p(cc)	60.45	60.00	61.00	61.00	70.50
Dynamic Viscosity ratio, R_v (μ_r/μ_d)	0.058	17.12	0.063	15.88	0.063
Immobile Water Saturation, Swc (%PV)	0.0	0.0	0.0	0.0	0.0

TABLE 2. Group #1 (continued).

PARAMETER	RUN #14 (core #6B)	RUN #19 (core #7B)	RUN #23 (core #6BW)	RUN #25 (Core #4BW)	RUN #27 (Core #5BW)
Type of Core	Berea Sandstone	Berea Sandstone	Berea Sandstone	Berea Sandstone	Berea Sandstone
Longitudinal dispersivity, α_d	6.30	0.11	0.39	0.78	0.62
Longitudinal dispersion coeff., K (cm^2/sec)	0.0292	0.00056	0.0083	0.0035	0.0096
Porosity, ϕ (%)	22.80	17.10	13.53	10.76	10.90
Permeability, k (mD)	680.00	8.40	455.00	8.50	197.00
Core Length, L (cm)	15.24	15.24	15.24	15.24	15.24
Average interstitial velocity, $\bar{U}$, (cm/sec)	0.0046	0.0051	0.0212	0.0045	0.0156
Pore Volume, V_p(cc)	70.50	52.92	41.80	33.25	33.80
Dynamic Viscosity ratio, R_v (μ_r/μ_d)	15.88	0.93	1.0645	1.0645	1.0645
Immobile Water Saturation, Swc (%PV)	0.0	0.0	47.80	43.70	45.30

TABLE 3. Experimental data and results obtained for Saint Peter sandstone cores (Length 6").

Group #2

PARAMETER	RUN #15 (core #8SP)	RUN #16 (core #11SP)	RUN #17 (core #9SP)	RUN #18 (Core #9ASP)
Type of Core	Saint Peter Sandstone	Saint Peter Sandstone	Saint Peter Sandstone	Saint Peter Sandstone
Longitudinal dispersivity, α_d	0.475	0.55	1.06	0.62
Longitudinal dispersion coeff., K (cm^2/sec)	0.0074	0.0085	0.0008	0.0021
Porosity, ϕ (%)	11.80	11.90	9.80	10.20
Permeability, k (mD)	2.10	3.00	1.60	1.60
Core Length, L (cm)	15.24	15.24	25.40	15.24
Average interstitial velocity, $\bar{U}$ (cm/sec)	0.0155	0.0154	0.0008	0.0034
Pore Volume, V_p(cc)	17.37	17.30	24.00	14.95
Dynamic Viscosity ratio, R_v (μ_r/μ_d)	1.00	1.00	1.00	1.00
Immobile Water Saturation, Swc (%PV)	0.0	0.0	0.0	0.0

TABLE 4. Experimental data and results obtained for consolidated and unconsolidated sandpacks (Length 9.5′ - 125′).

Group #3

PARAMETER	RUN #33A (core #C1)	RUN #33B (core #C1)	RUN #33C (core #C2)	RUN #33D (Core #C2)
Type of Core	Consolidated Sandpack	Consolidated Sandpack	Consolidated Sandpack	Consolidated Sandpack
Longitudinal dispersivity, α_d	16.65	19.51	26.25	22.88
Longitudinal dispersion coeff., K (cm^2/sec)	6.39	4.58	2.17	2.09
Porosity, ϕ (%)	32.00	32.00	32.00	32.00
Permeability, k (mD)	910.00	910.00	910.00	910.00
Core Length, L (cm)	2286.00	2286.00	3810.00	3810.00
Average interstitial velocity, $\bar{U}$ (cm/sec)	0.3837	0.2347	0.0815	0.0913
Pore Volume, V_p(cc)	702.25	702.25	1170.00	1170.00
Dynamic Viscosity ratio, R_v (μ_r/μ_d)	17.23	17.23	17.23	17.23
Immobile Water Saturation, S_{wc} (%PV)	0.0736	0.0755	0.0704	0.0736

TABLE 4. Group #3 (continued).

PARAMETER	RUN #33E (core #C2)	RUN #33F (core #C2)	RUN #1 (core #3P)	RUN #2 (Core #2P)	RUN #3 (Core #4P)
Type of Core	Consolid. Sandpack	Consolid. Sandpack	Unconsolid Sandpack	Unconsolid Sandpack	Unconsolid Sandpack
Longitudinal dispersivity, α_d	46.97	63.47	30.76	21.34	14.97
Longitudinal dispersion coeff., K (cm^2/sec)	5.51	6.62	9.69	8.93	6.045
Porosity, ϕ (%)	32.00	32.00	18.60	34.60	9.0
Permeability, k (mD)	910.00	910.00	481.00	2466.00	325.00
Core Length, L (cm)	3810.00	3810.00	285.60	280.52	285.60
Average interstitial velocity, $\bar{U}$ (cm/sec)	0.1173	0.1043	0.3150	0.4183	0.4038
Pore Volume, V_p(cc)	1170.00	1170.00	50.36	93.20	24.80
Dynamic Viscosity ratio, R_v (μ_r/μ_d)	17.23	17.23	1.10	1.10	1.05
Immobile Water Saturation, S_{wc} (%PV)	0.0634	0.0608	0.0	0.0	0.0

TABLE 5. Experimental data and results obtained for plug samples from Chancellor #1 (Length 2").

FIELD DATA ON PLUG SAMPLES:

Location: SW1/4 SE1/4 NW1/4 NW1/4, Sec. 16, T10N, R3E
Pottawatomie County, Oklahoma

Completion: in Red Fork sand between 4848'-4856'

Date: October 7, 1981

Initial Production: 368 BOPD+166 McfGPD + 37 BWPD

Group #4

RUN NO./ PLUG NO.	WELL DEPTH	K (cm^2/sec)	α_d (cm)	k mD	ϕ %
35/P1	4829'	0.003045	0.157	18.0	13.98
36/P2	4830'	0.003899	0.210	13.0	14.39
37/P3	4831'	0.002253	0.136	26.0	15.63
38/P4	4831.9'	0.003337	0.186	14.0	14.82
39/P5	4832'	0.001042	0.053	8.80	11.93
40/P6	4833'	0.006074	0.325	29.0	13.98
41/P7	4834'	0.009237	0.357	26.0	9.85
42/P8	4835'	0.003380	0.201	58.0	15.63
43/P9	4836'	0.002161	0.121	33.17	16.07
47/P11	4838.6'	0.003224	0.223	35.0	18.12
48/P12	4839.1'	0.004622	0.202	72.0	11.90
52/P19	4846.5'	0.018261	0.804	6.45	13.15
53/P20	4847.5'	0.001924	0.085	225.0	15.20
54/P21	4848.9'	0.005722	0.250	125.0	16.90

TABLE 6. Experimental Results*

Run#/ Core#	ϕ (%)	k (mD)	α_d (cm)	K (cm^2/sec)	H	Pe	R_v	S_{wc} (%PV)
4/1B	22.6	225	6.17	0.023	2.00	2.27	17.12	0.0
5/2B	22.6	15	1.45	0.006	2.37	9.65	17.12	0.0
6/3B	18.1	90	0.37	0.002	1.93	41.21	1.00	0.0
7/3B	18.1	90	3.3	0.017	2.20	4.62	17.12	0.0
8/3B	18.1	90	0.07	0.0004	3.30	206.0	0.06	0.0
9/4B	19.6	98	0.08	0.0004	3.40	193.6	0.06	0.0
10/4B	19.6	98	3.39	0.017	1.72	4.50	17.12	0.0
11/5B	19.8	143	0.12	0.0056	5.57	12.84	0.06	0.0
12/5B	19.8	143	3.93	0.0196	2.26	3.88	15.88	0.0
13/6B	22.8	680	0.13	0.0006	3.30	105.8	0.06	0.0
14/6B	22.8	680	6.30	0.0292	2.00	2.42	15.88	0.0
15/8SP	11.8	2.1	0.03	0.0005	4.60	32.11	1.00	0.0
16/11SP	11.9	3.0	0.55	0.0085	3.70	27.61	1.00	0.0
17/9SP	9.8	1.6	1.06	0.0008	4.20	25.40	1.00	0.0
18/9A	10.2	1.6	0.62	0.0021	3.00	24.38	1.00	0.0
19/7B	17.1	8.4	0.11	0.0006	1.80	136.7	1.00	0.0
23/6BW	13.5	455	0.39	0.0083	4.00	39.06	1.00	47.8
25/4BW	10.8	8.5	0.77	0.0035	3.70	19.60	1.00	43.7
27/5BW	10.9	197	0.62	0.0096	3.20	24.70	1.00	45.3

Note: Runs #22, 24, and 26 were conducted as a part of saturation.

* ϕ = Porosity
K = Dispersion coefficient
α_d = Dispersivity
H = Koval's Heterogeneity factor
Pe = Peclet number
R_v = Viscosity ratio (r/ d)
S_{wc} = Immobile water saturation
k = Total permeability of the core

TABLE 7. Variation of permeability, dispersion coefficient and dispersivity with average grain diameter.

Run/ Core	Permeability k (mD)	Dispersion Coefficient K (cm^2/sec)	α_d (cm)	Ave. Grain Diameter d_{gr} (mm)	Grain Diameter ϕ-scale	Viscosity Ratio R_v (μ_r/μ_d)
7/3B	90	0.0165	3.30	0.200	2.322	17.12
10/4B	98	0.0167	3.39	0.210	2.252	17.12
12/5B	143	0.0206	4.13	0.244	2.035	17.12*
14/6B	680	0.0292	6.30	0.254	1.977	17.12

*corrected

TABLE 8. Experimental and predicted standard dispersion coefficients for Berea sandstone core.

Parameter	Run #6	Run #7	Run #8
$\mu_{displacing}$, cp	0.642	0.473	8.1
$\mu_{resident}$, cp	0.642	8.1	0.473
Viscosity ratio, R_v	1.0	17.125	0.058
Standard Dispersion coefficient, K_s cm^2/sec (calculated by eq. 8)	0.0022	0.00218	0.0027
Dispersion coefficient K, cm^2/sec (experimental)	0.0022	0.0165	0.00037

Parameter	Run #9	Run #10	Run #11	Run #12
$\mu_{displacing}$, cp	8.1	0.473	8.1	0.51
$\mu_{resident}$, cp	0.473	8.1	0.51	8.1
Viscosity ratio, R_v	0.058	17.12	0.063	15.88
Standard Dispersion coefficient, K_s cm^2/sec (calculated by eq. 8)	0.00278	0.0022	0.0039	0.0027
Dispersion coefficient K, cm^2/sec (experimental)	0.00037	0.0167	0.00056	0.01963

TABLE 9. Dispersivity data.

Data Point	Y	X1	X2	X3	X4	X5	X6
1	0.15700	18.00	14.70	0.172332	3.303	0.0022912	0.002447
2	0.21050	13.00	13.40	0.154734	2.810	0.0026656	0.003899
3	0.13574	26.00	17.90	0.218026	2.040	0.0025951	0.002253
4	0.18575	14.00	14.82	0.173984	2.150	0.0025296	0.00337
5	0.05262	8.80	15.54	0.183992	3.380	0.0023647	0.001042
6	0.32493	29.00	17.09	0.206127	2.360	0.0026139	0.006074
7	0.35740	26.00	9.85	0.109262	2.390	0.0025459	0.009237
8	0.28651	26.00	9.85	0.109262	4.260	0.0029646	0.008623
9	0.20104	58.00	15.63	0.185255	2.000	0.0026280	0.003380
10	0.27912	58.00	15.16	0.185255	2.300	0.0006037	0.004809
11	0.12081	33.17	16.06	0.191327	2.140	0.0028739	0.002141
12	0.22340	35.00	18.12	0.221299	1.833	0.0026148	0.003224
13	0.20417	52.90	11.90	0.135073	2.658	0.0027195	0.004665
14	0.06263	100.00	13.15	0.151410	2.476	0.0027178	0.001294
15	0.80415	6.25	13.15	0.151410	3.531	0.0024503	0.014984
16	0.08524	225.00	15.20	0.179245	2.182	0.0029755	0.001668
17	0.25051	125.00	16.90	0.203369	2.383	0.0027837	0.004126
18	0.11602	190.00	16.50	0.197604	2.156	0.0031366	0.002205
19	0.19793	150.00	16.07	0.191469	2.427	0.0030286	0.003730
20	6.17000	225.00	22.60	0.291989	2.000	0.0008429	0.023000
21	1.45000	15.00	22.60	0.291989	2.370	0.0008588	0.006000
22	3.30000	90.00	18.10	0.221001	2.200	0.0009050	0.017000
23	3.39000	98.00	19.60	0.243781	1.720	0.0009662	0.017000
24	3.93000	143.00	19.80	0.246882	2.260	0.0009900	0.019600
25	6.30000	680.00	22.80	0.295336	2.000	0.0010488	0.029200
26	0.07000	90.00	18.10	0.221001	3.300	0.0090500	0.000400
27	0.08000	98.00	19.60	0.243781	3.400	0.0009212	0.000400
28	0.12000	143.00	19.80	0.246882	5.570	0.0009405	0.005600
29	0.13000	680.00	22.80	0.295336	3.300	0.0009576	0.000600
30	0.37000	90.00	18.10	0.221010	1.930	0.0010769	0.002000
31	0.11000	8.40	17.10	0.206272	1.800	0.0008721	0.000600
32	0.14200	300.00	21.50	0.273885	1.750	0.0047945	0.003168
33	0.47700	163.00	18.90	0.233045	1.720	0.0046788	0.011810
34	0.07839	68.00	20.20	0.253132	2.000	0.0009437	0.000366
35	0.09000	250.00	21.70	0.277139	1.570	.	0.001900
36	0.01893	215.00	20.30	0.254705	1.776	.	0.011640
37	0.09888	93.00	17.20	0.207729	1.251	.	0.003610

TABLE 10. Correlation Matrix

Y	1.0000						
X1	0.3944	1.0000					
X2	0.4249	0.5774	1.0000				
X3	0.4394	0.5951	0.9987	1.0000			
X4	-0.1853	-0.0747	-0.2479	-0.2434	1.0000		
X5	-0.3606	-0.1060	-0.2308	-0.2434	0.0287	1.0000	
X6	0.8958	0.3295	0.2507	0.2675	-0.1155	-0.2842	1.0000
	Y	X1	X2	X3	X4	X5	X6

TABLE 11. Table of means, standard deviation, minimum and maximum.

variables	mean	standard deviation	n	minimum	maximum	skewness
X1	125.5060	155.1220	37	6.4500	680.0000	2.6289
X2	17.3457	3.4204	37	9.8500	22.9000	-0.2992
X3	21.2036	4.9640	37	10.9262	29.5336	-0.1193
X4	2.4512	0.8342	37	1.2510	5.5700	1.8203
X5	2.3221	1.6157	34	0.6037	9.0500	2.2749
X6	6.4063	1.6186	37	0.3660	29.2000	1.6983
Y	0.8265	1.6186	37	0.0189	6.3000	2.5603

NOMENCLATURE:
Y = Dispersivity
X1 = Permeability
X2 = Porosity
X3 = Void ratio
X4 = Heterogeneity
X5 = Darcy velocity
X6 = Dispersion coefficient

TABLE 12. Data for box and whiskers plot of the variables.

	PERCENTILE MARKS				
	95%	75%	50%	25%	5%
X1	680.0000	156.5000	90.0000	26.0000	8.2050
X2	22.4000	19.8000	17.2000	15.1800	9.8500
X3	29.5336	24.6882	20.7792	18.1618	10.9262
X4	4.3910	2.7340	2.2000	1.9650	1.5381
X5	5.8584	2.8063	2.5378	0.9541	0.7831
X6	23.6200	8.9300	3.6100	1.9500	0.3966
Y	6.1830	0.3637	0.1979	0.1044	0.0493

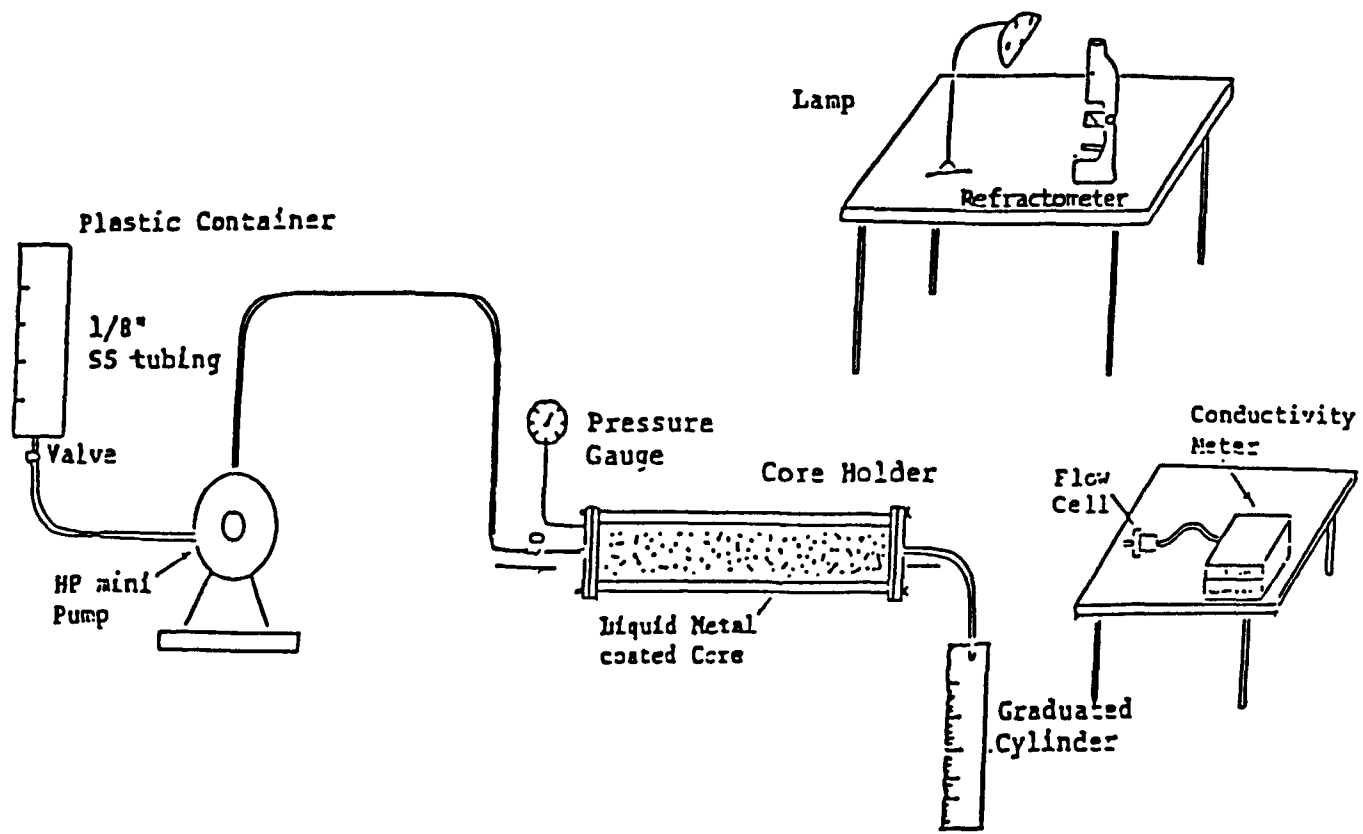

Figure 1. Schematic Diagram of the Experimental Setup

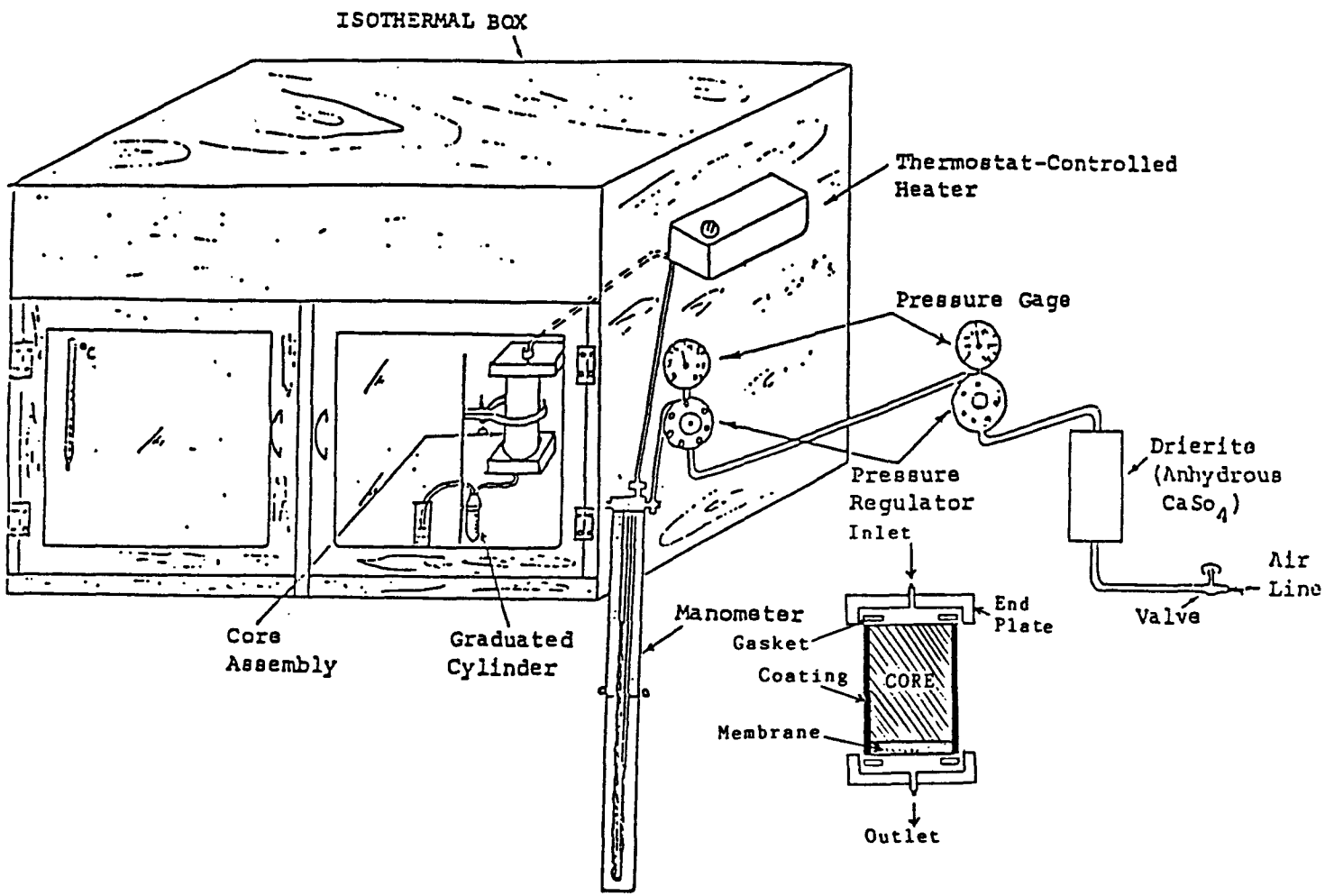

Figure 2. Capillary Pressure Schematic Diagram

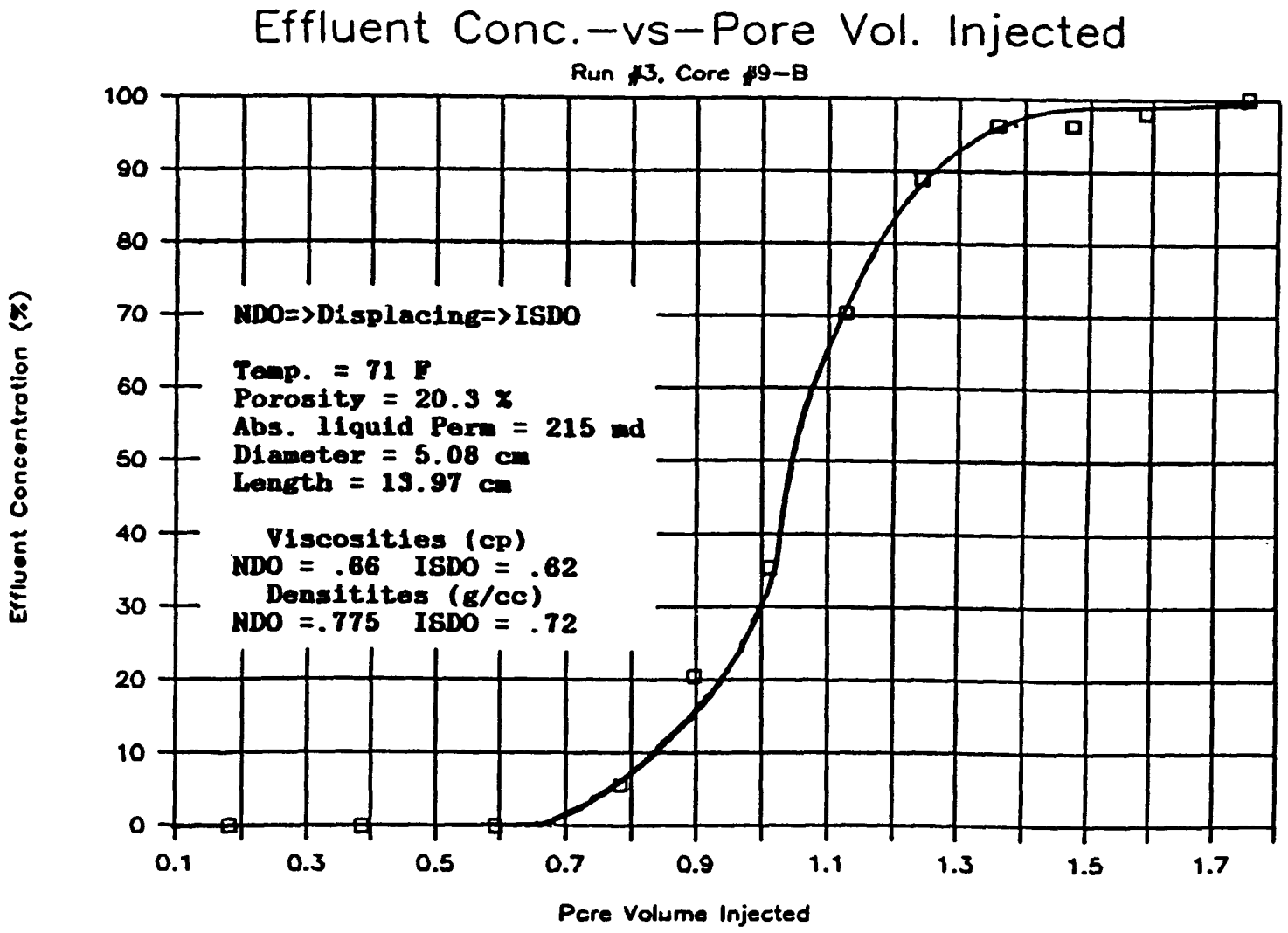

Figure 3. Effluent Concentration vs. Pore Volumes Injected for Run #3

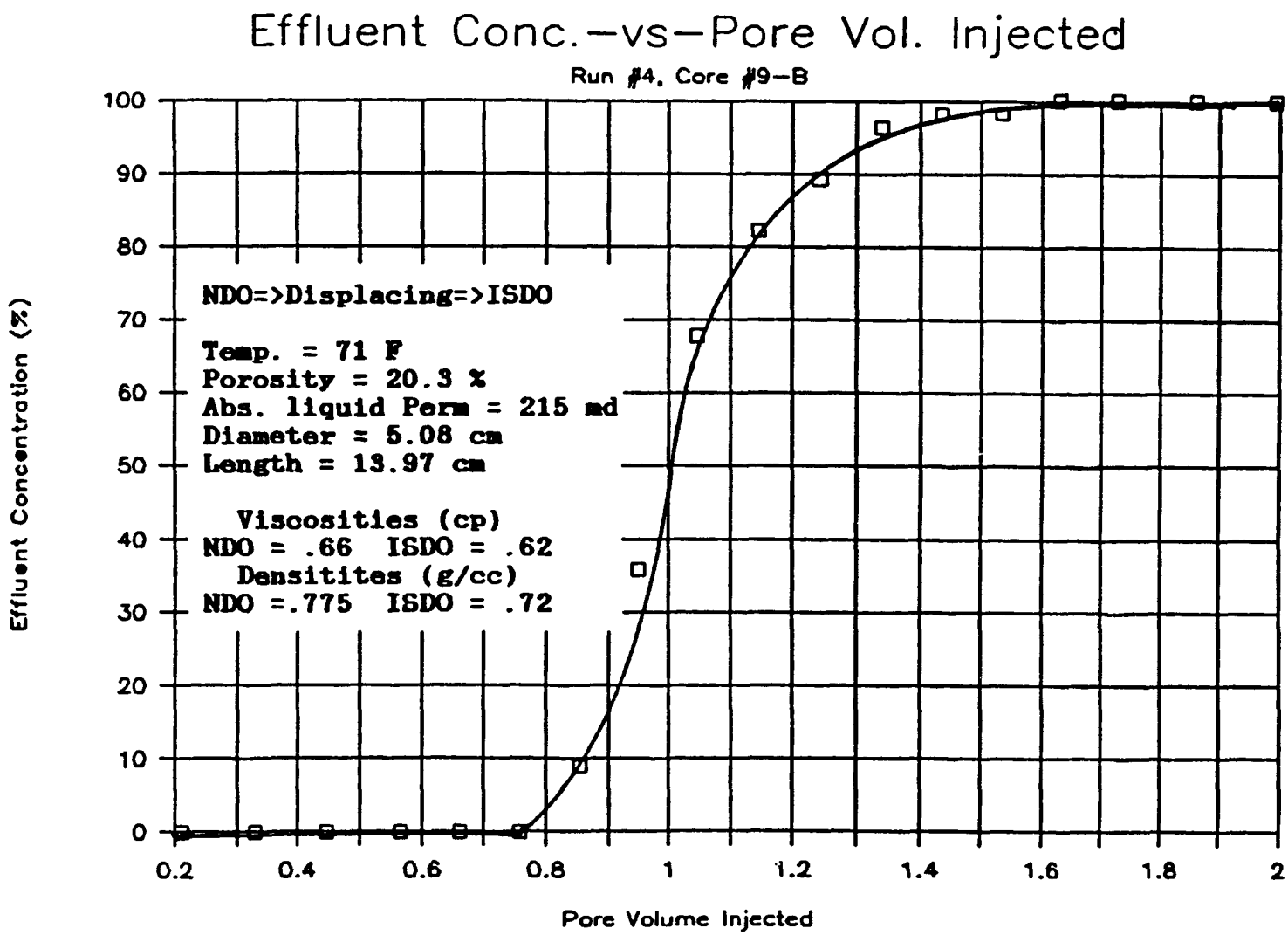

Figure 4. Effluent Concentration vs. Pore Volumes Injected for Run #4

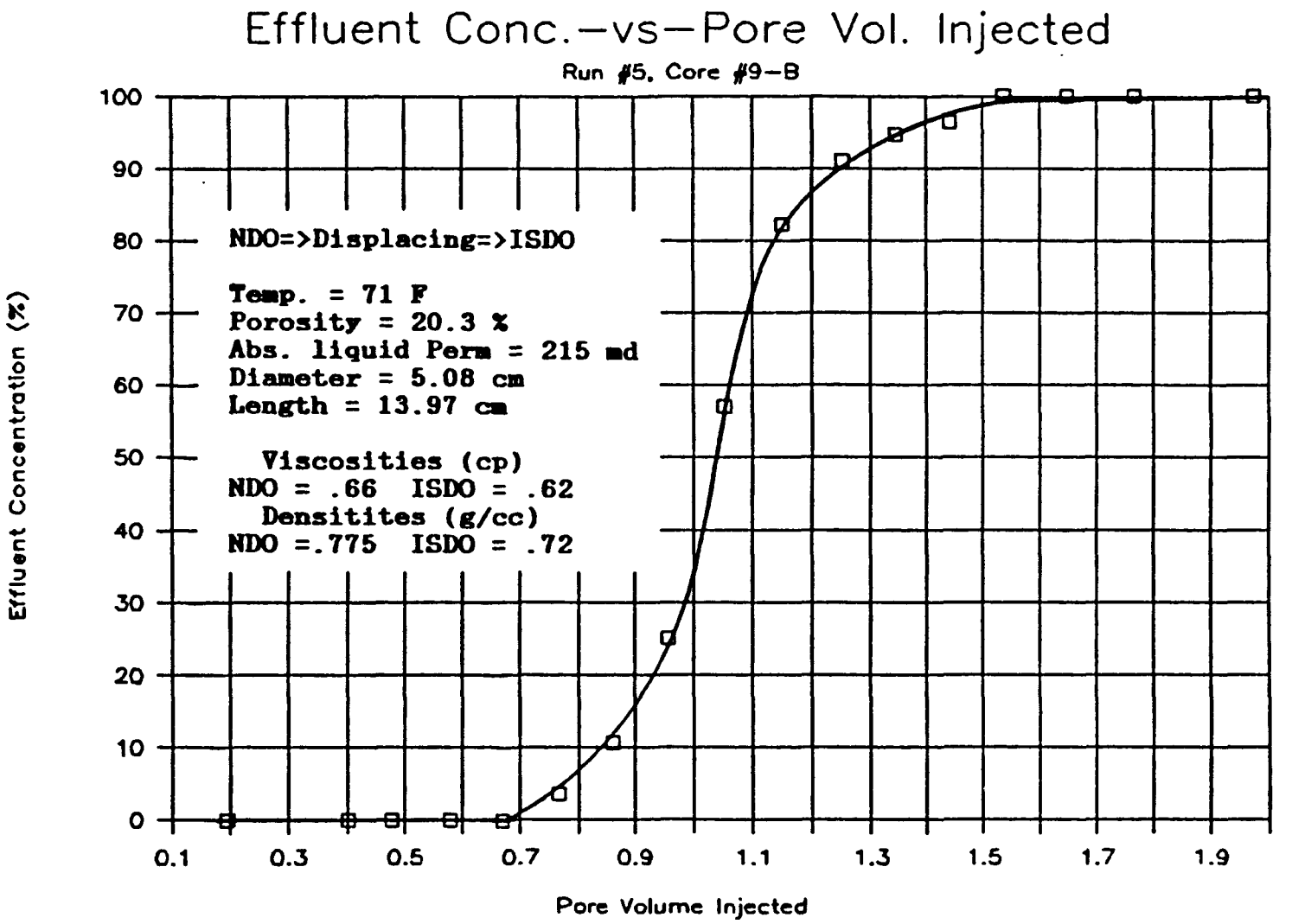

Figure 5. Effluent Concentration vs. Pore Volumes Injected for Run #5

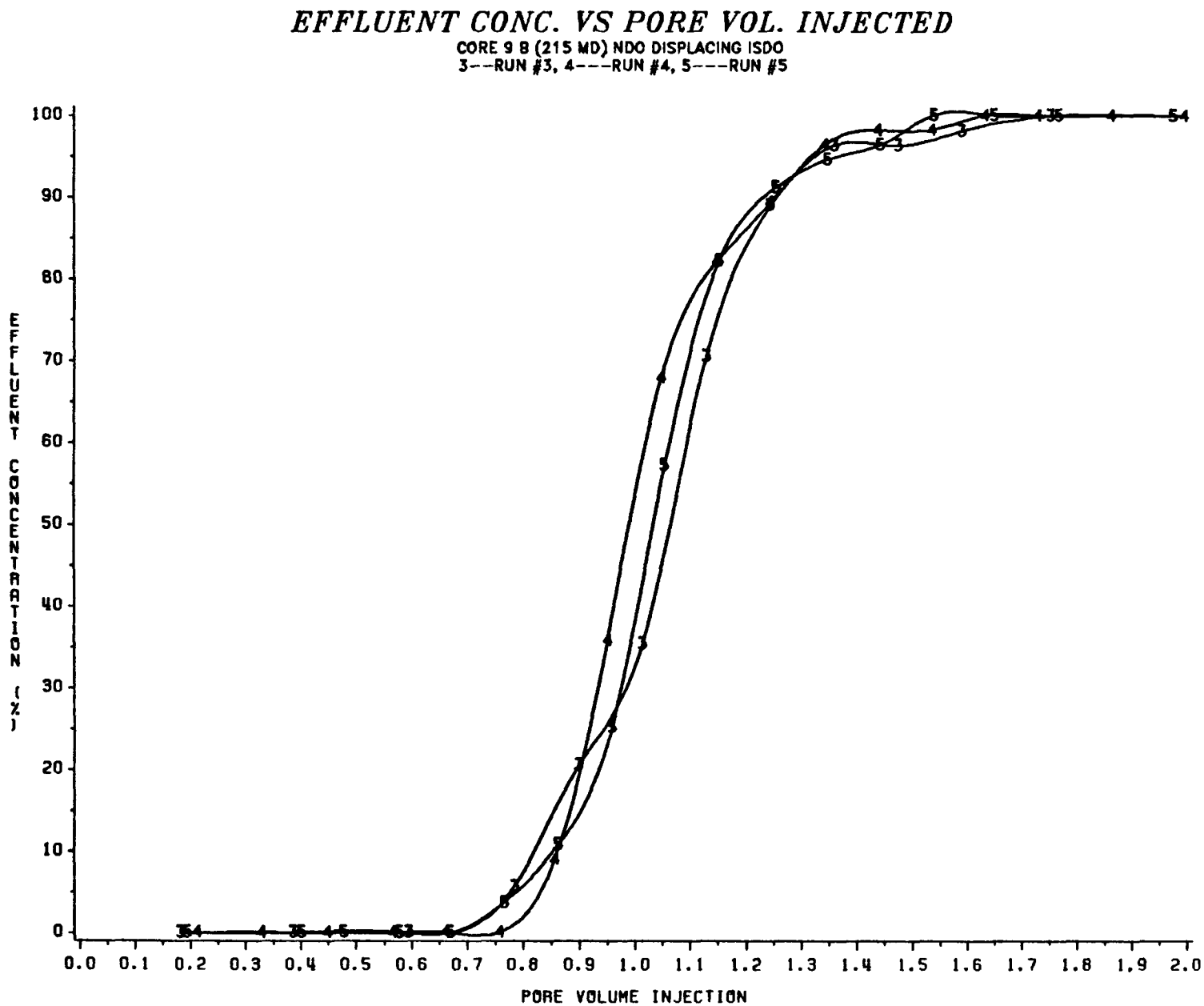

Figure 6. Effluent Concentration vs. Pore Volumes Injected for Runs #3, 4, 5

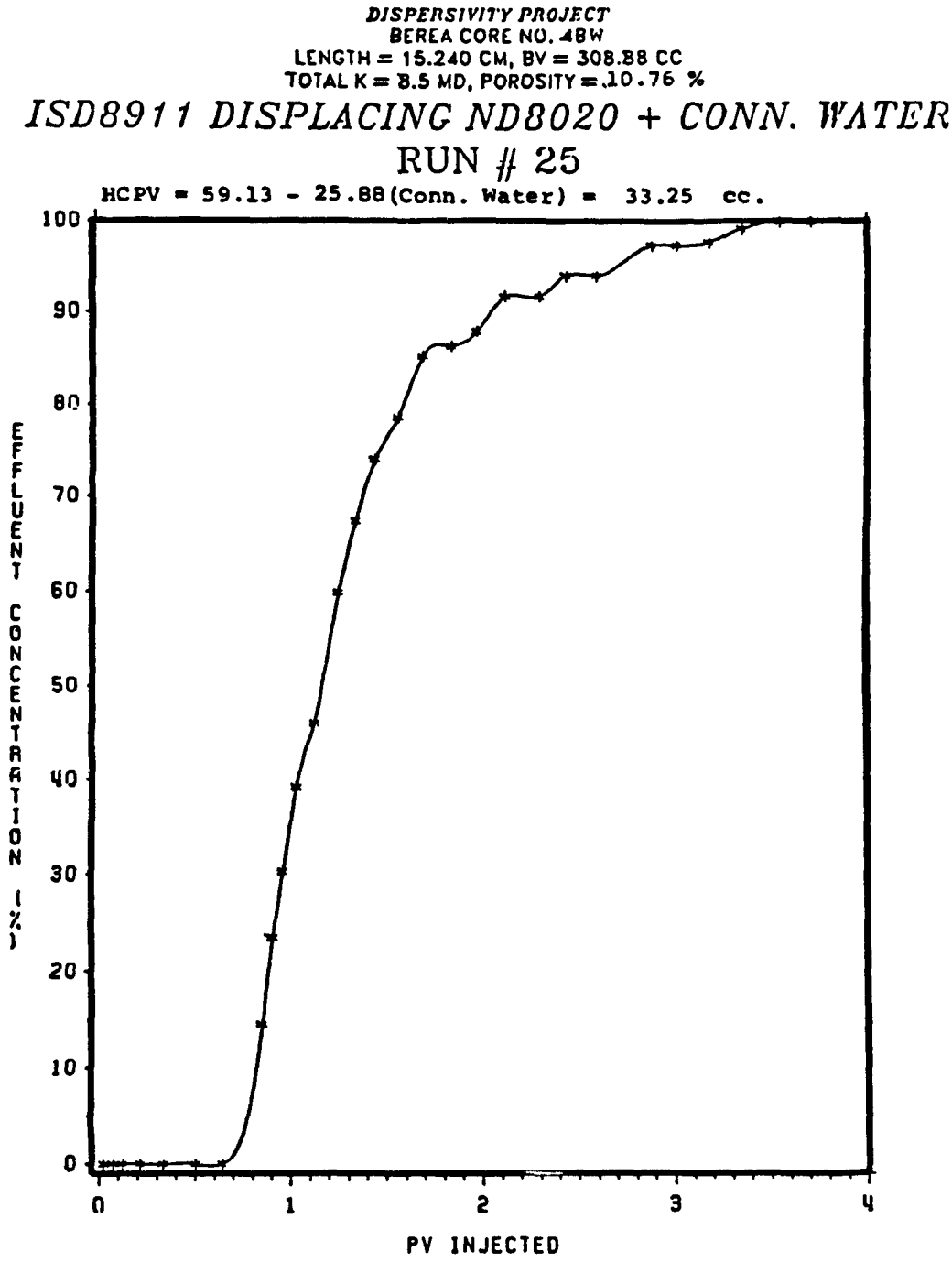

Figure 7. Effluent Concentration vs. Pore Volumes Injected for Run #25

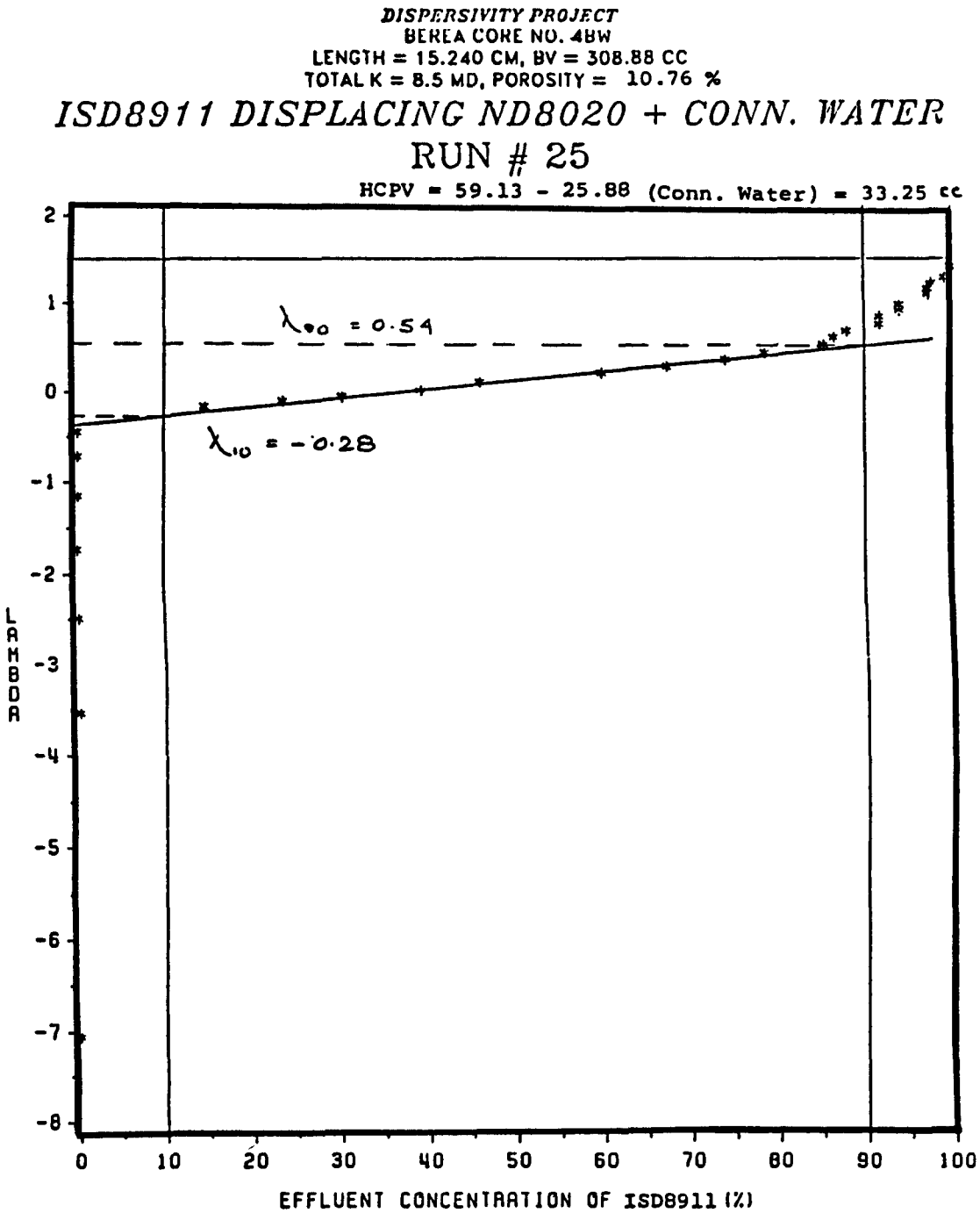

Figure 8. Lambda vs. Effluent Concentration for Run #25

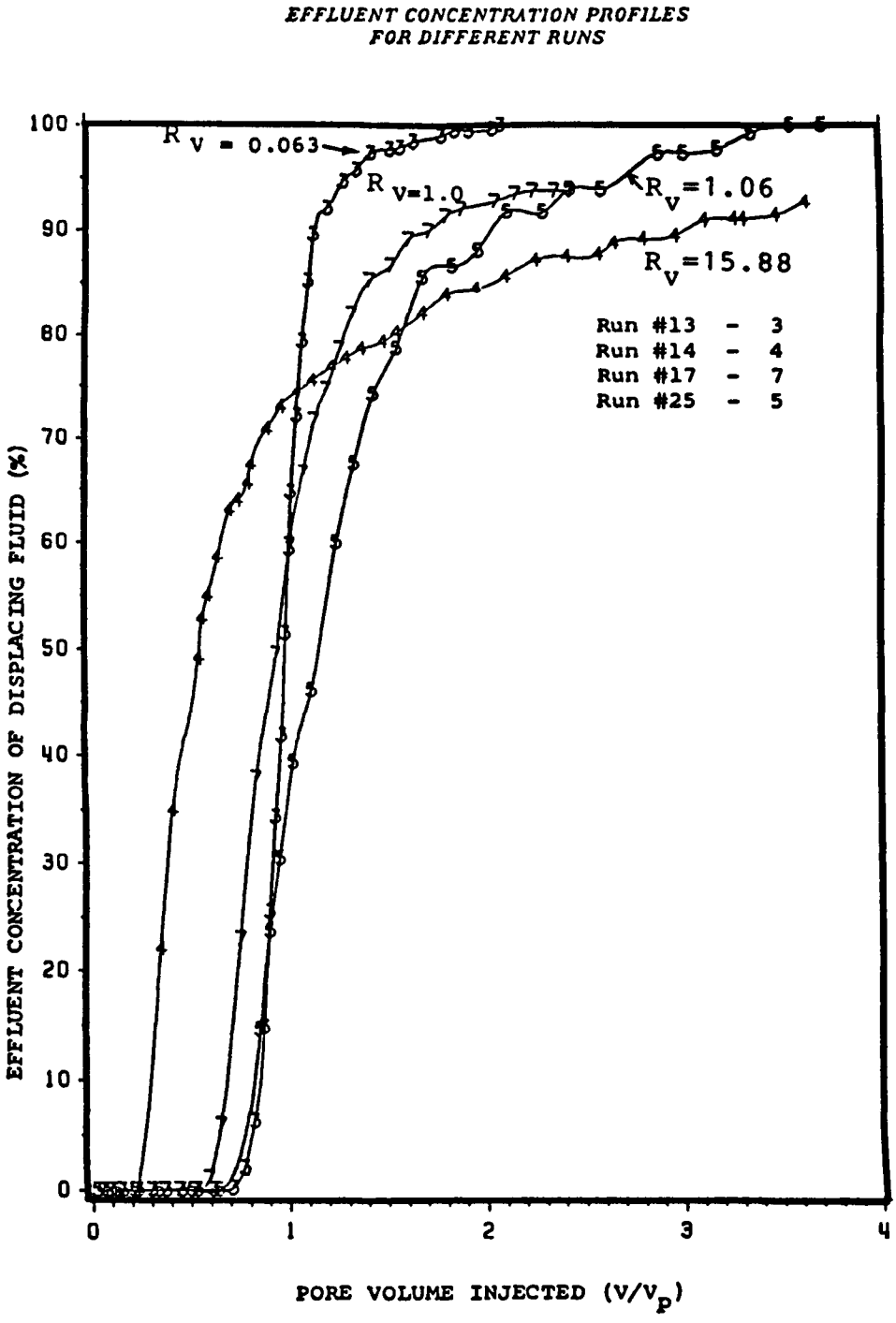

Figure 9. Effluent Concentration vs. Pore Volumes Injected for Runs #13, 14, 17, 25

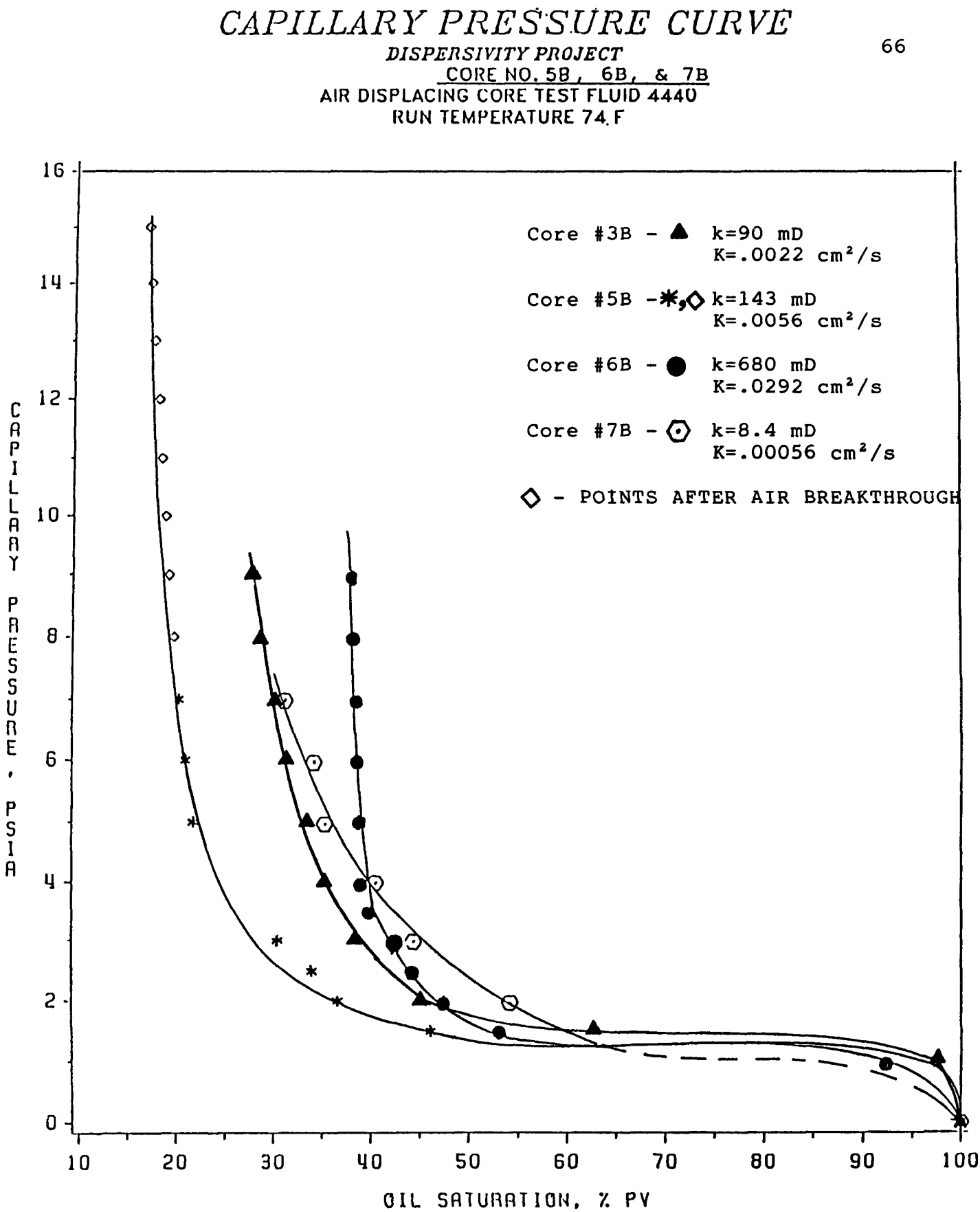

Figure 10. Capillary Pressure Curves for Cores #3B, 5B, 6B, 7B

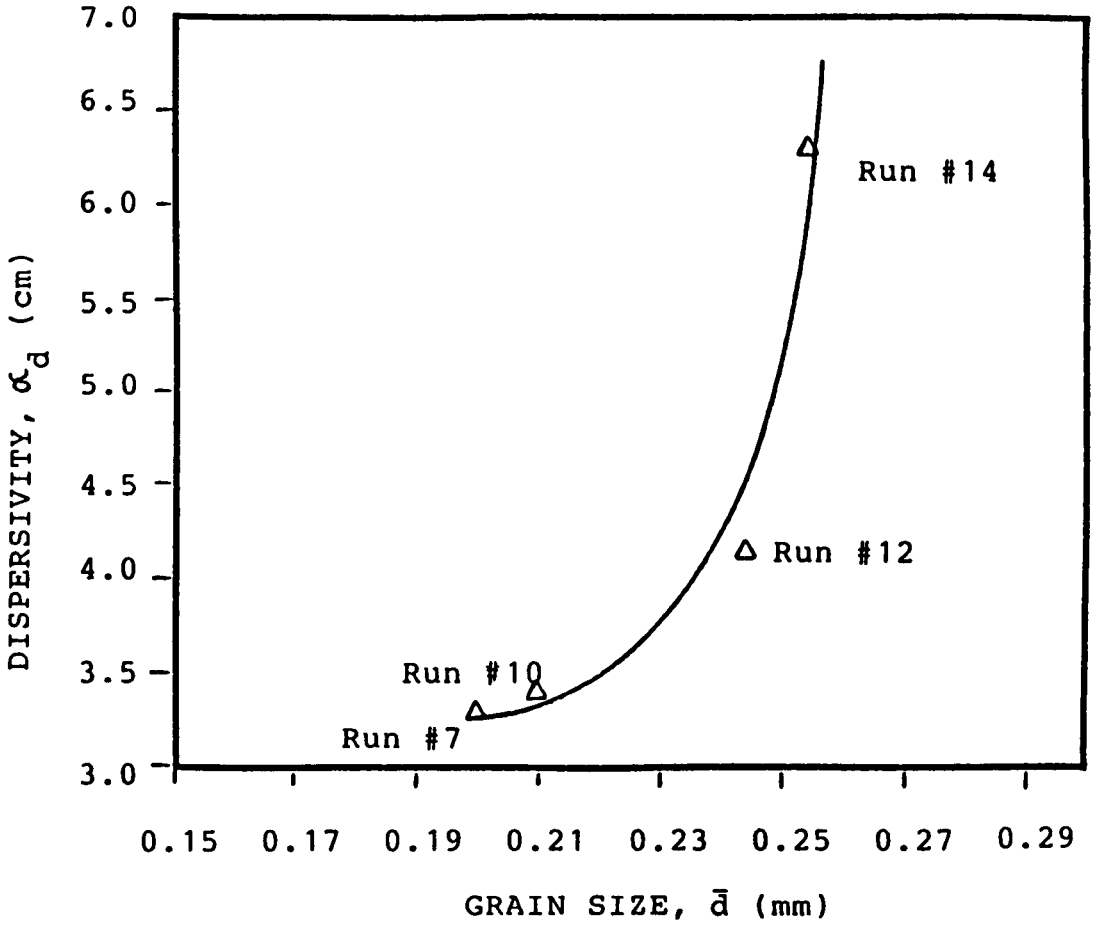

Figure 11. Dispersivity vs. Grain Diameter for Several Berea Sandstone Cores

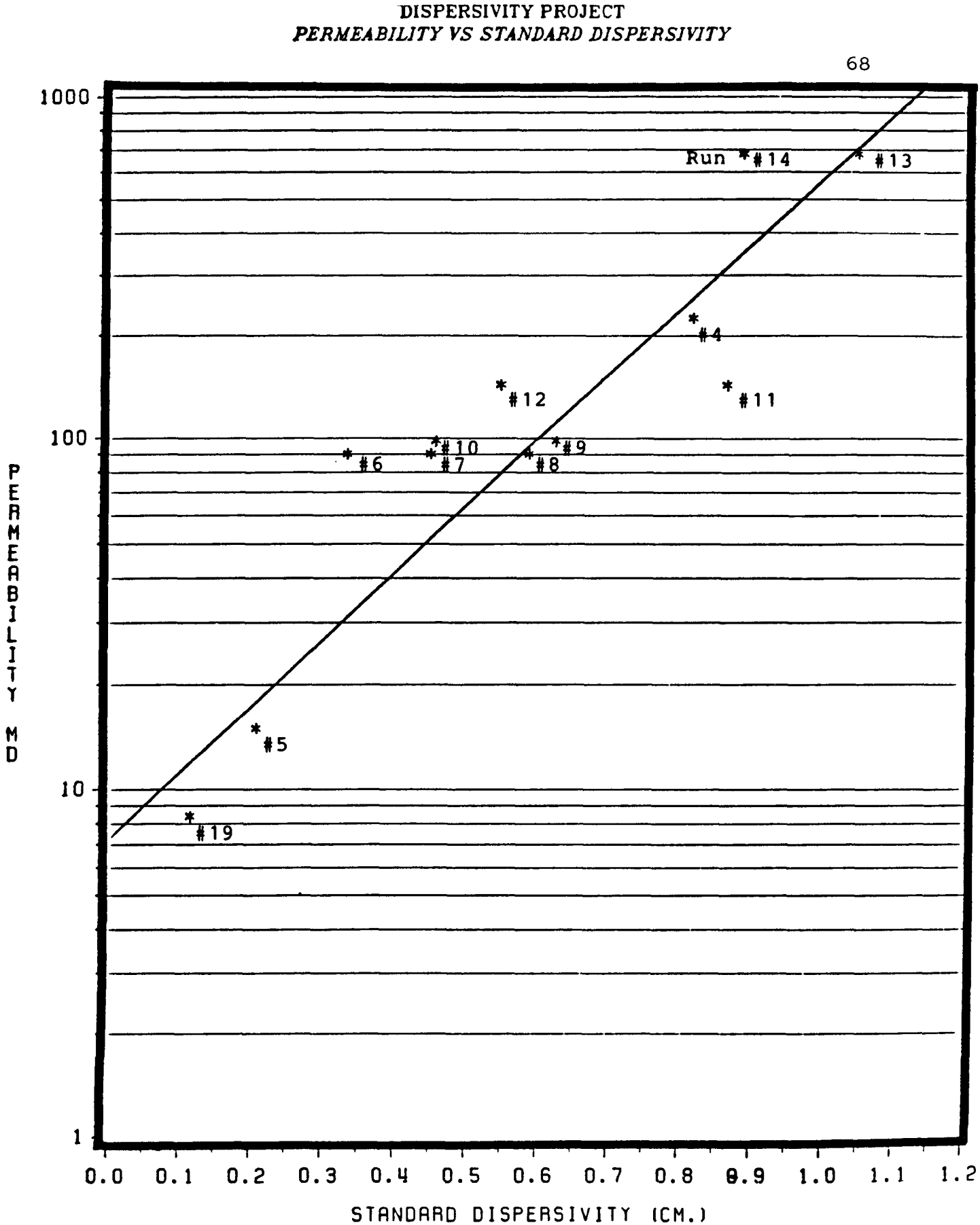

Figure 12. Permeability vs. Standard Dispersivity

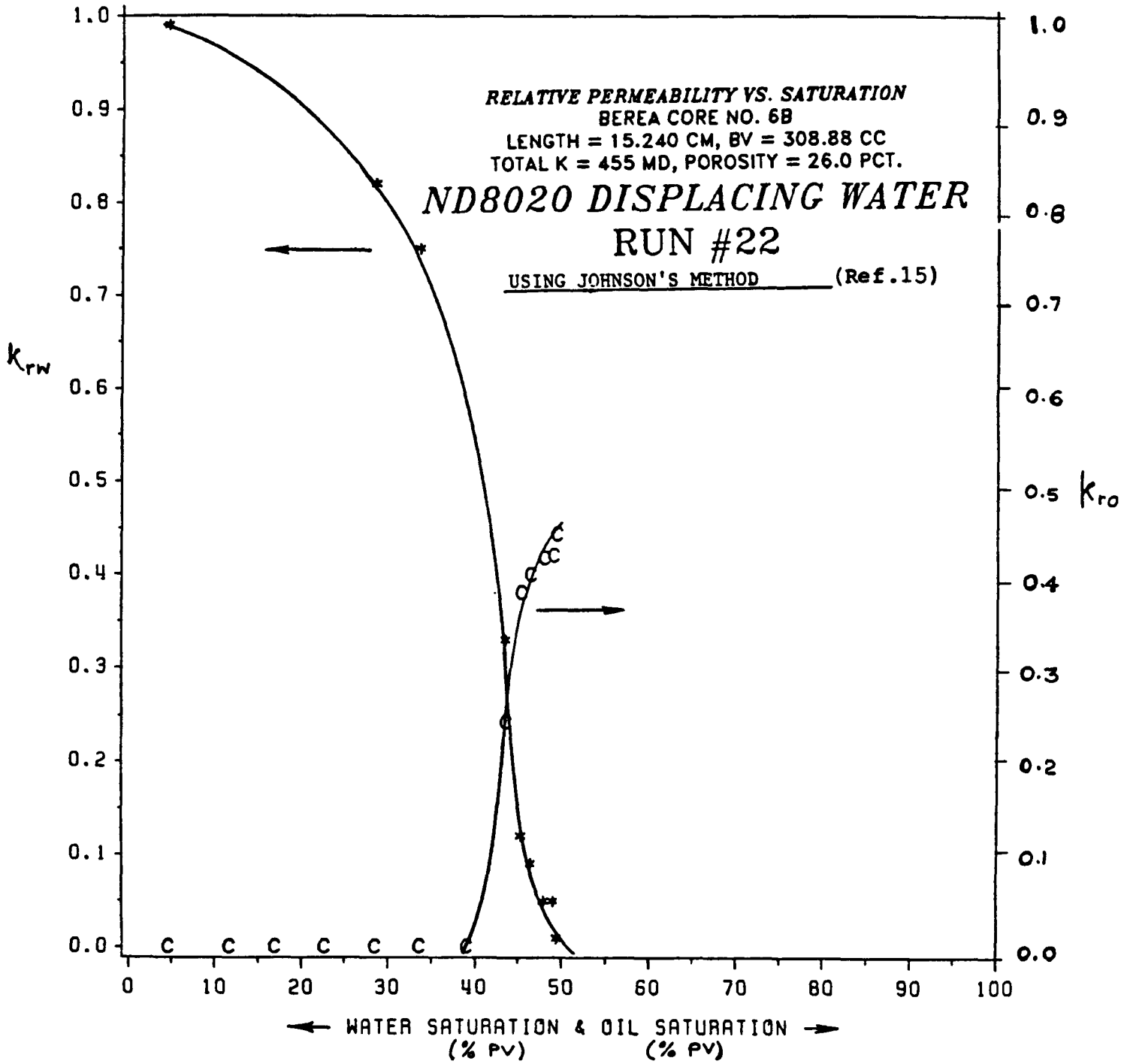

Figure 13. Relative Permeability Curve for Run #22 (Johnson's Method)

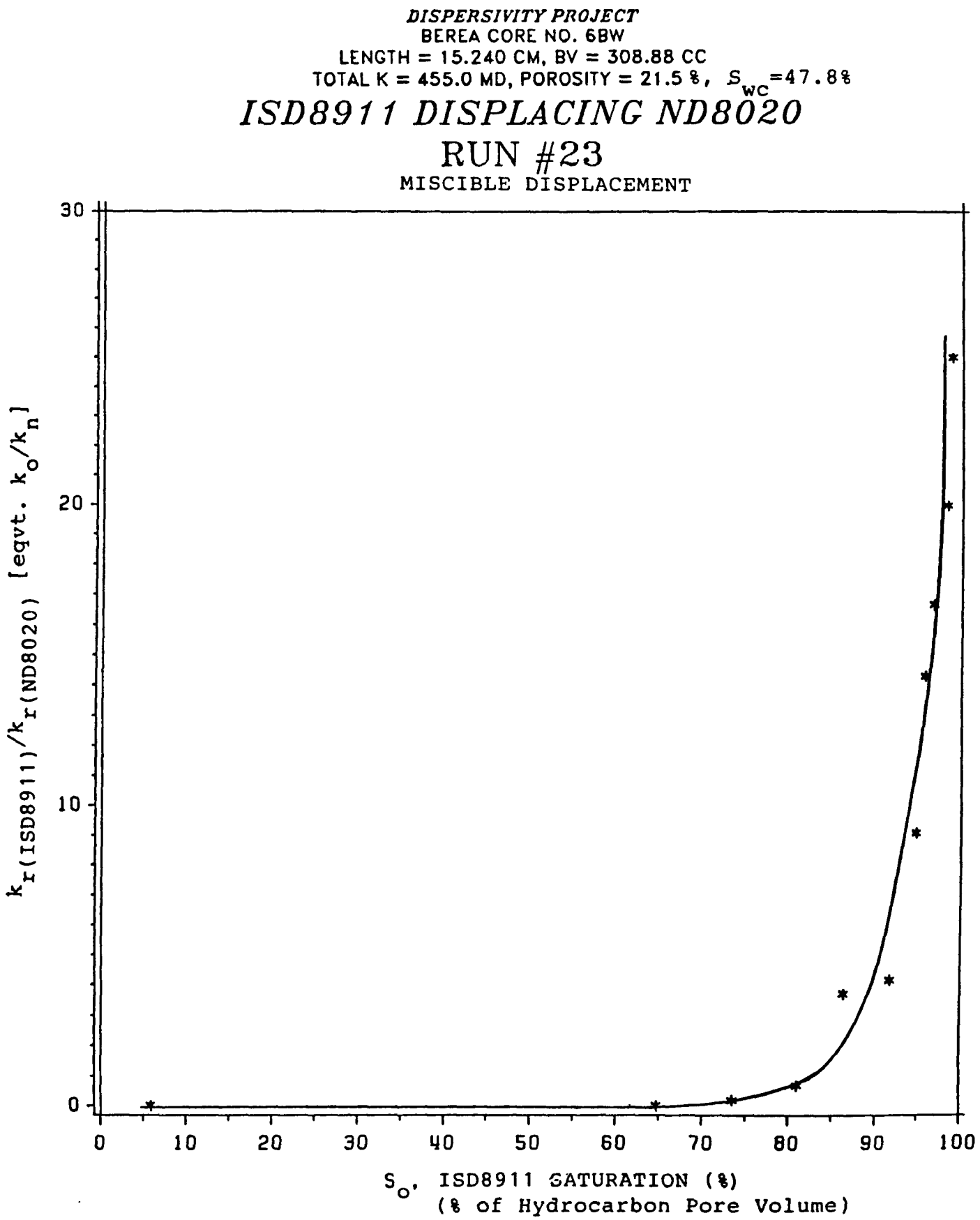

Figure 14. Permeability Ratio vs. Saturation for Run #23

DISPERSIVITY PROJECT

BEREA CORE NO. 3B
LENGTH = 15.24 CM, BV = 308.89 CC
TOTAL K = 90 MD, POROSITY = 18.1 PCT.
CRUDE OIL DISPLACING NAPHTHA

RUN NO. 8

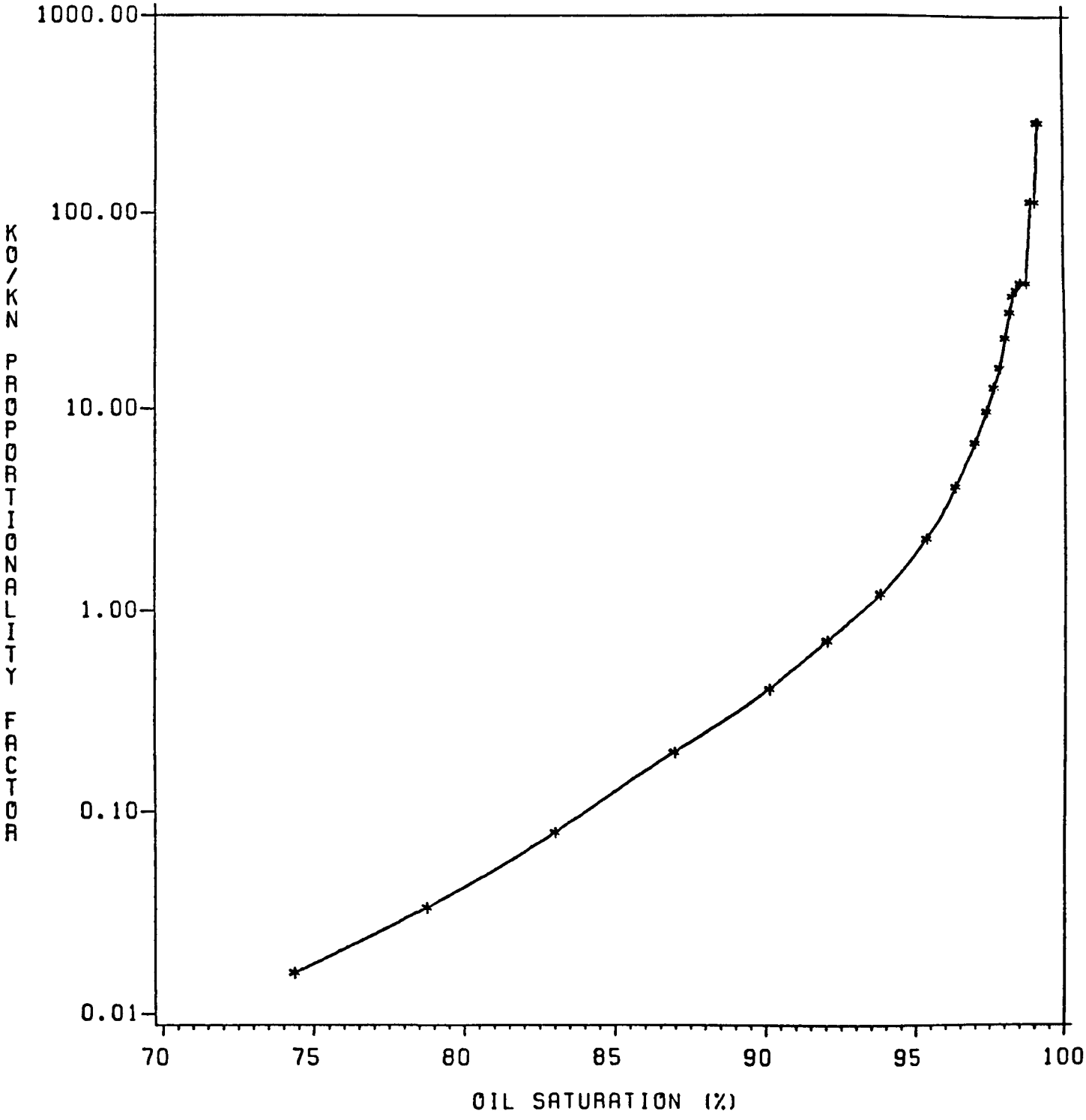

Figure 15. Pseudo Permeability Ratio vs. Saturation for Run #8

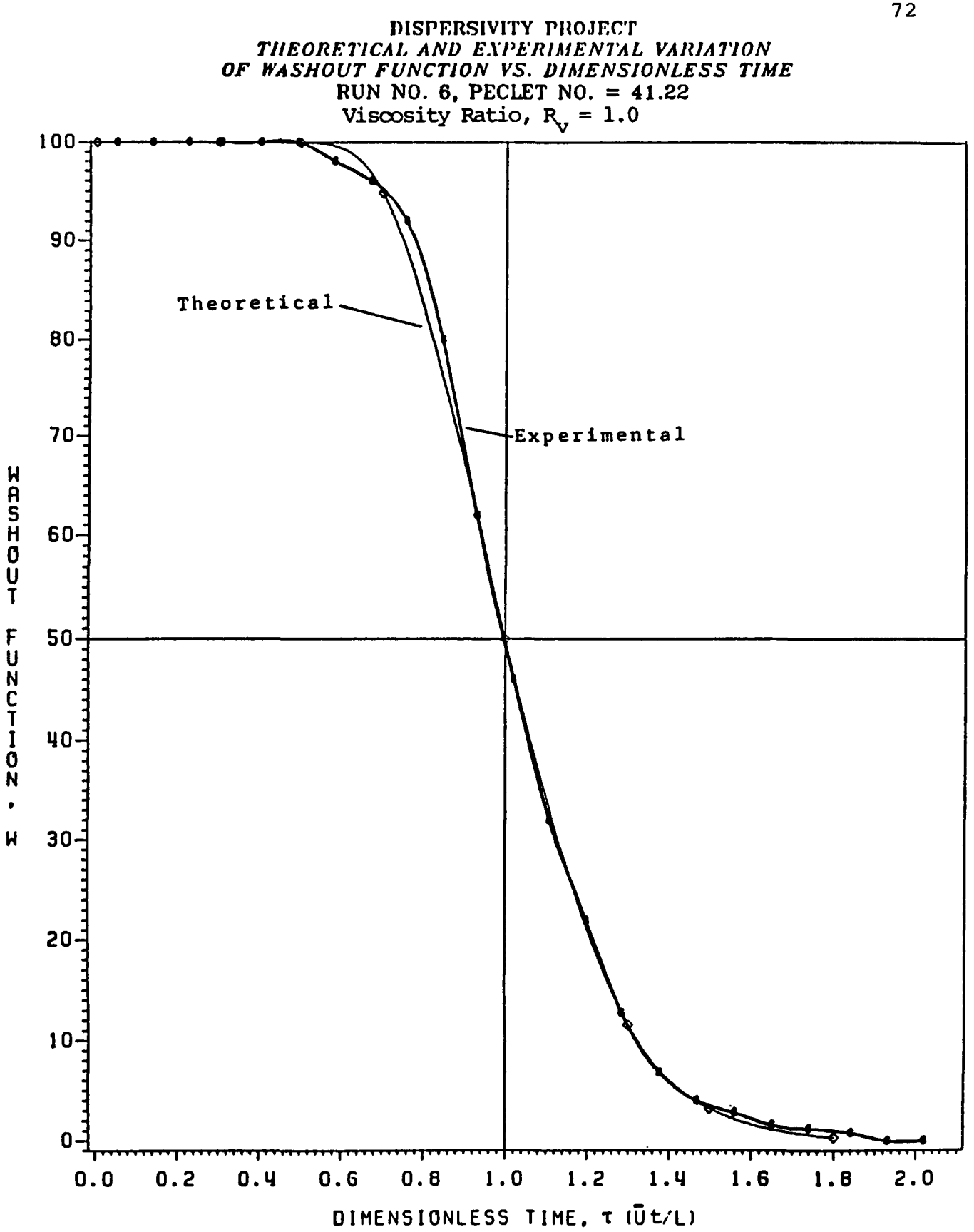

Figure 16. Theoretical and Experimental Washout Functions vs. Dimensionless Time for Run #6

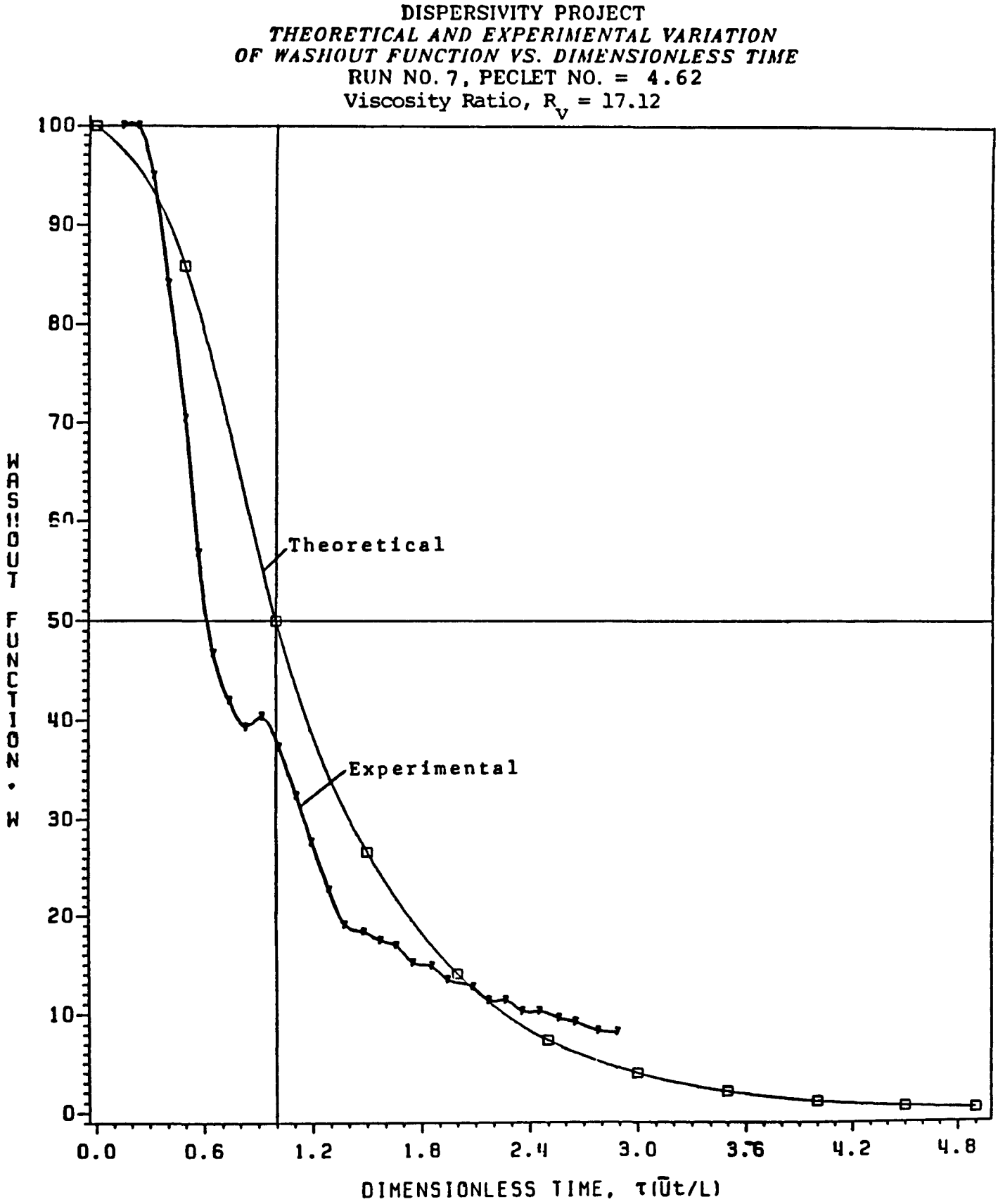

Figure 17. Theoretical and Experimental Washout Functions vs. Dimensionless Time for Run #7

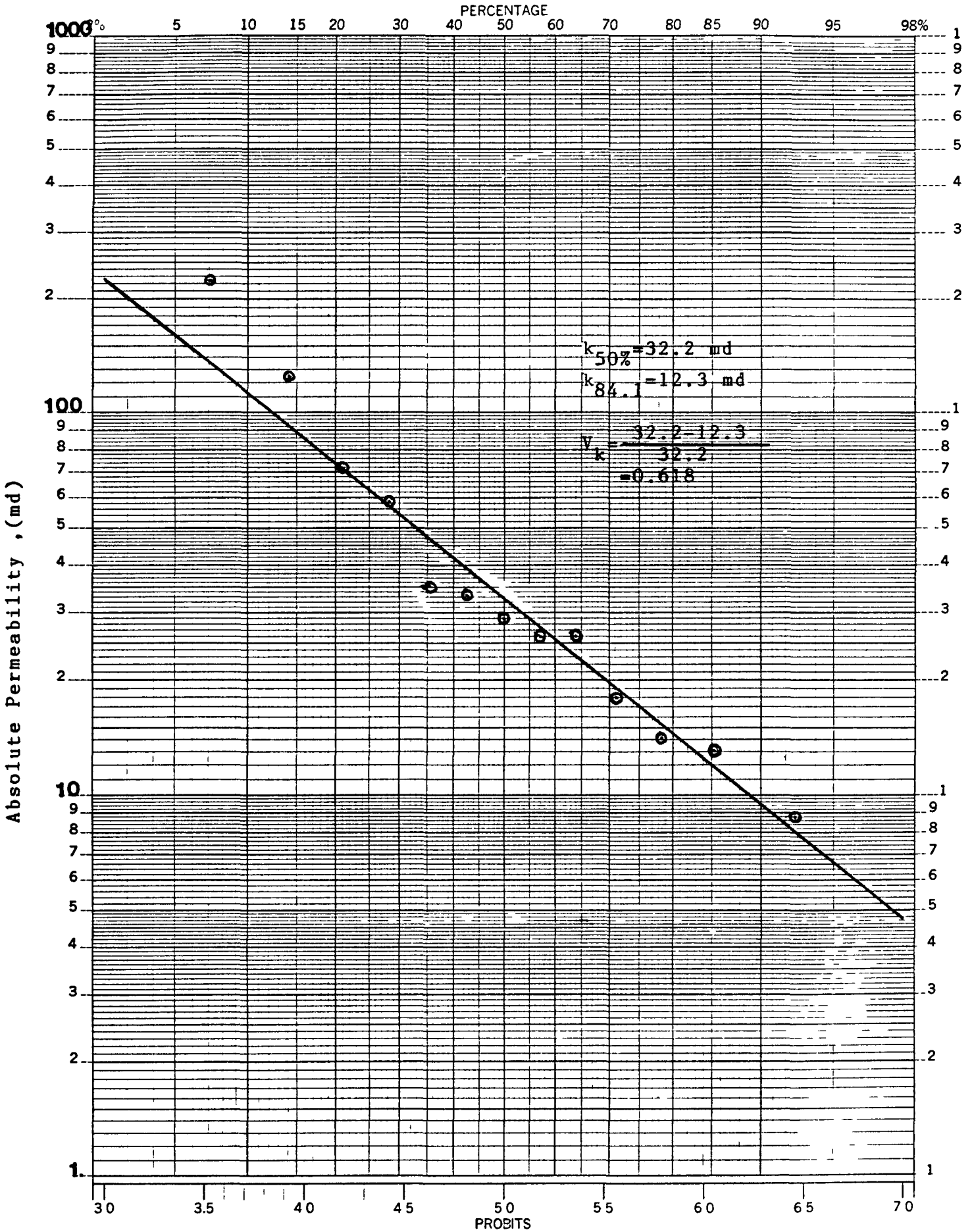

Figure 18. Log-Probability Plot of Permeability

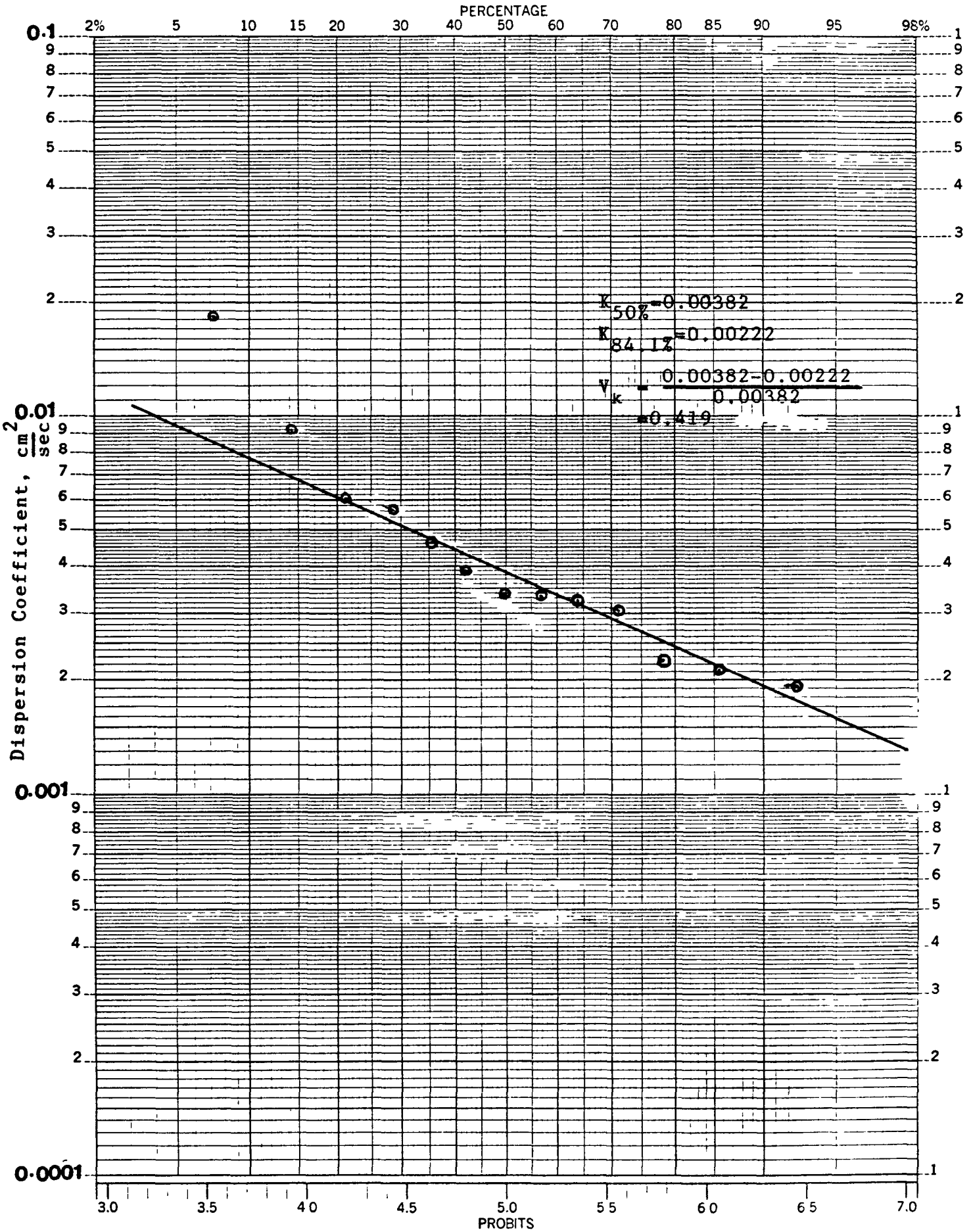

Figure 19. Log-Probability Plot of Dispersion Coefficient

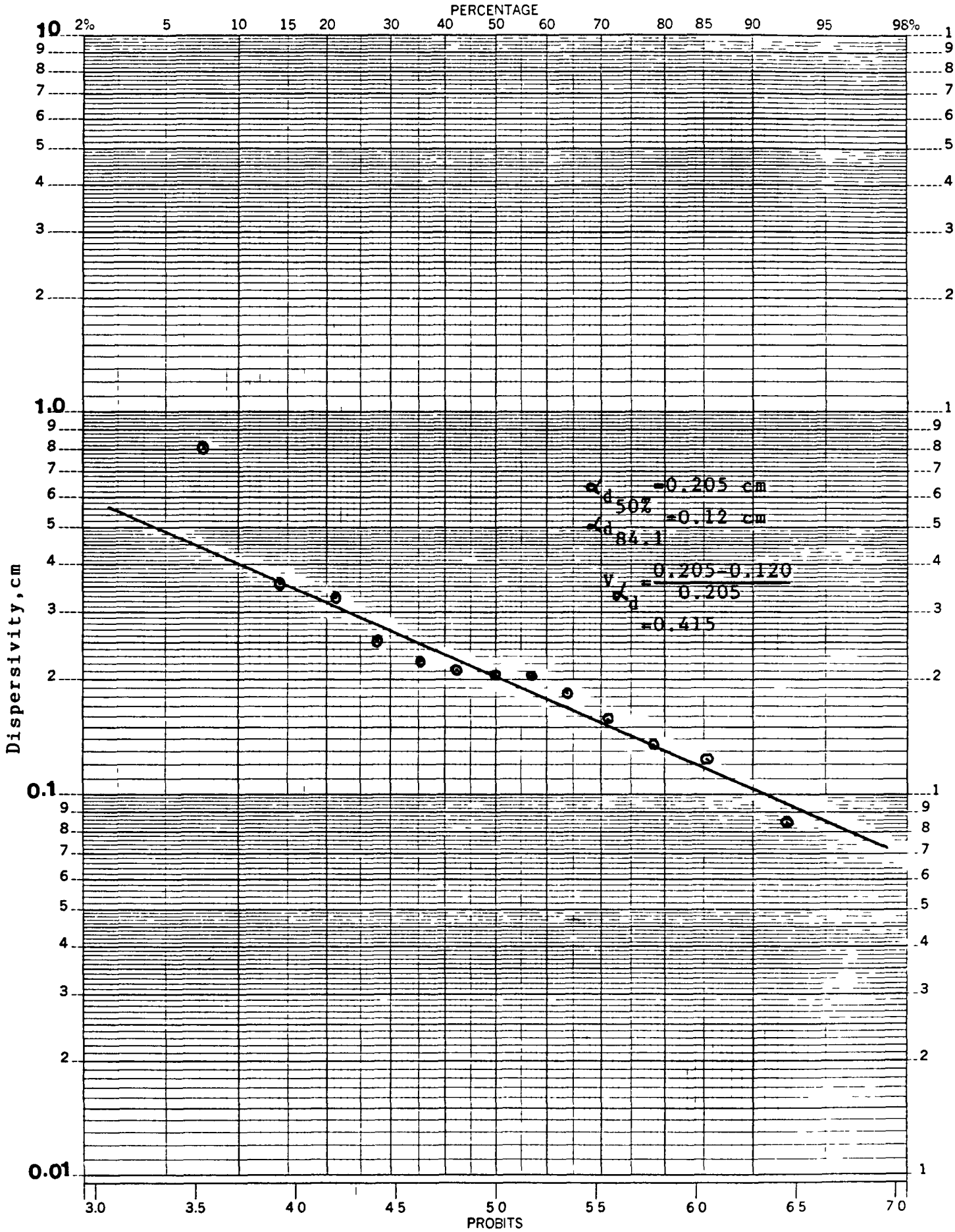

Figure 20. Log-Probability Plot of Dispersivity

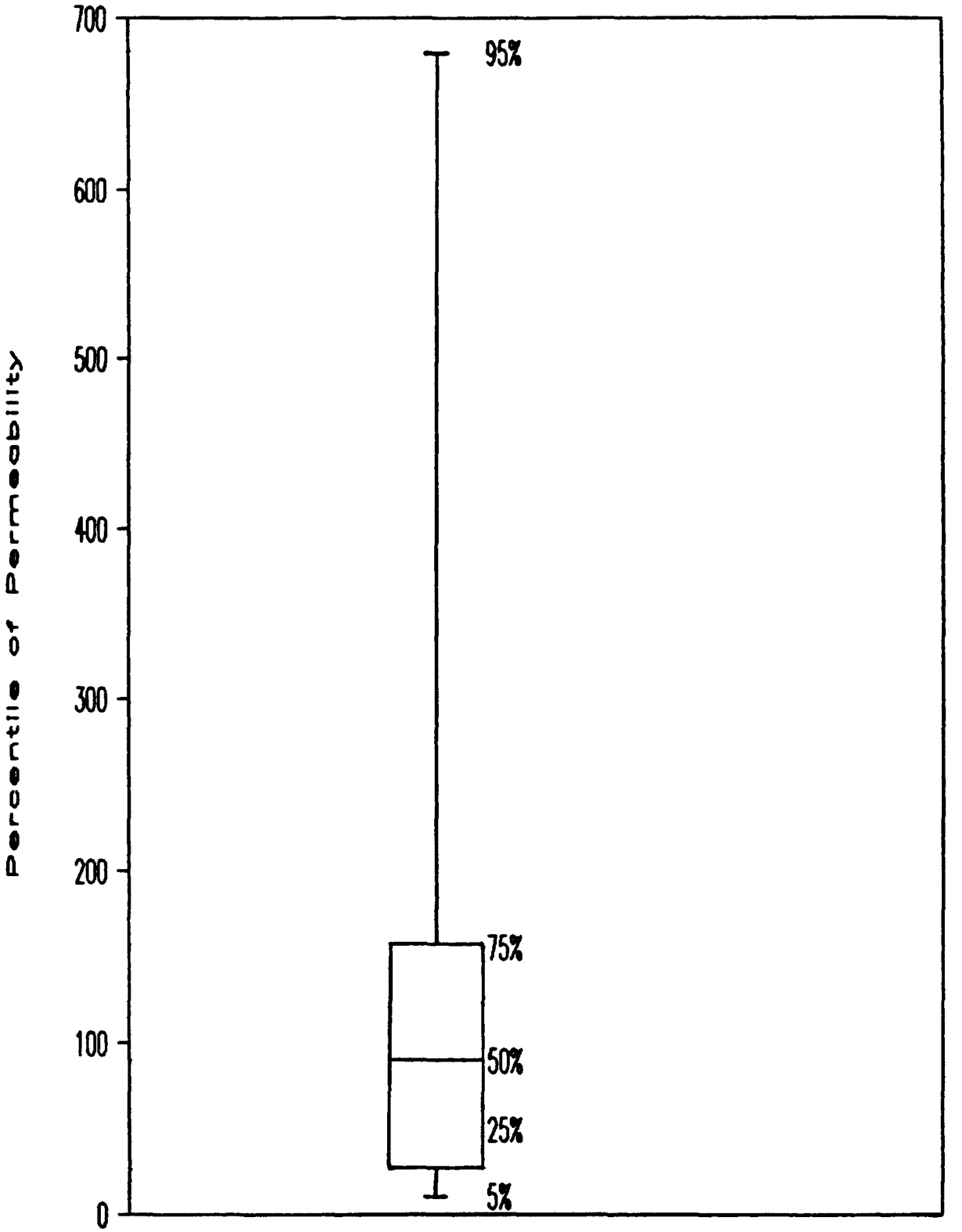

Figure 21. Box and Whiskers Plot of Permeability

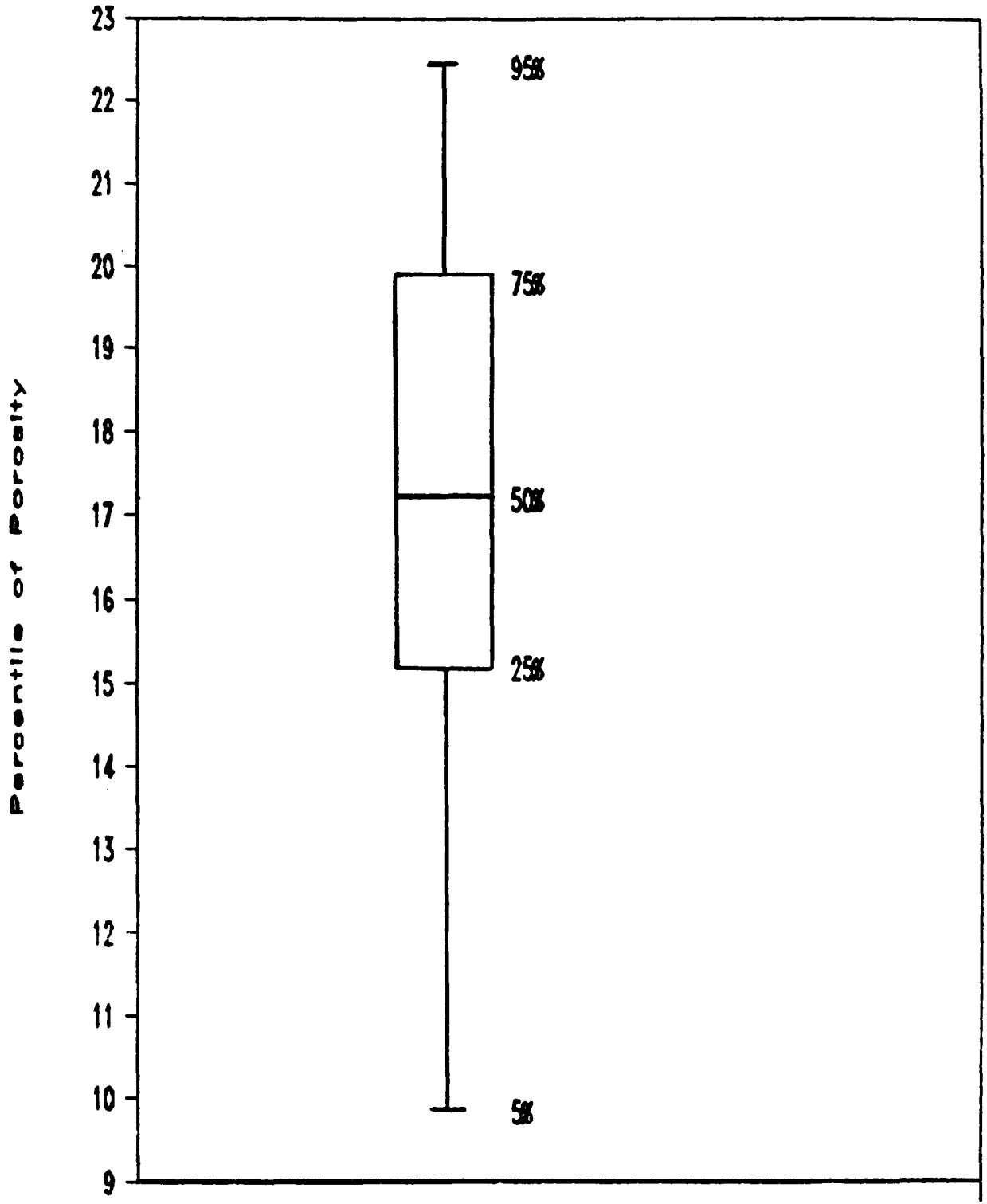

Figure 22. Box and Whiskers Plot of Porosity

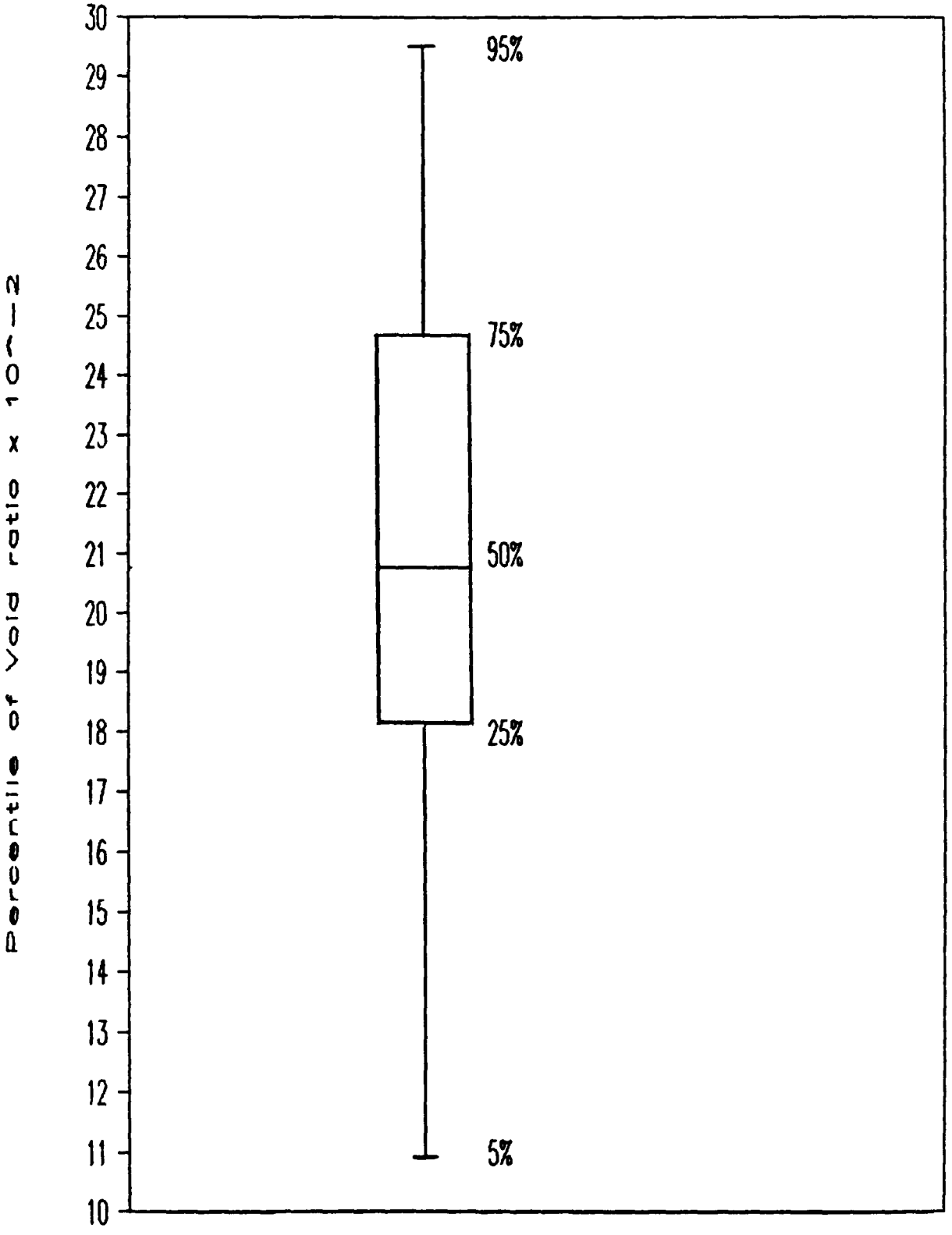

Figure 23. Box and Whiskers Plot of Void Ratio

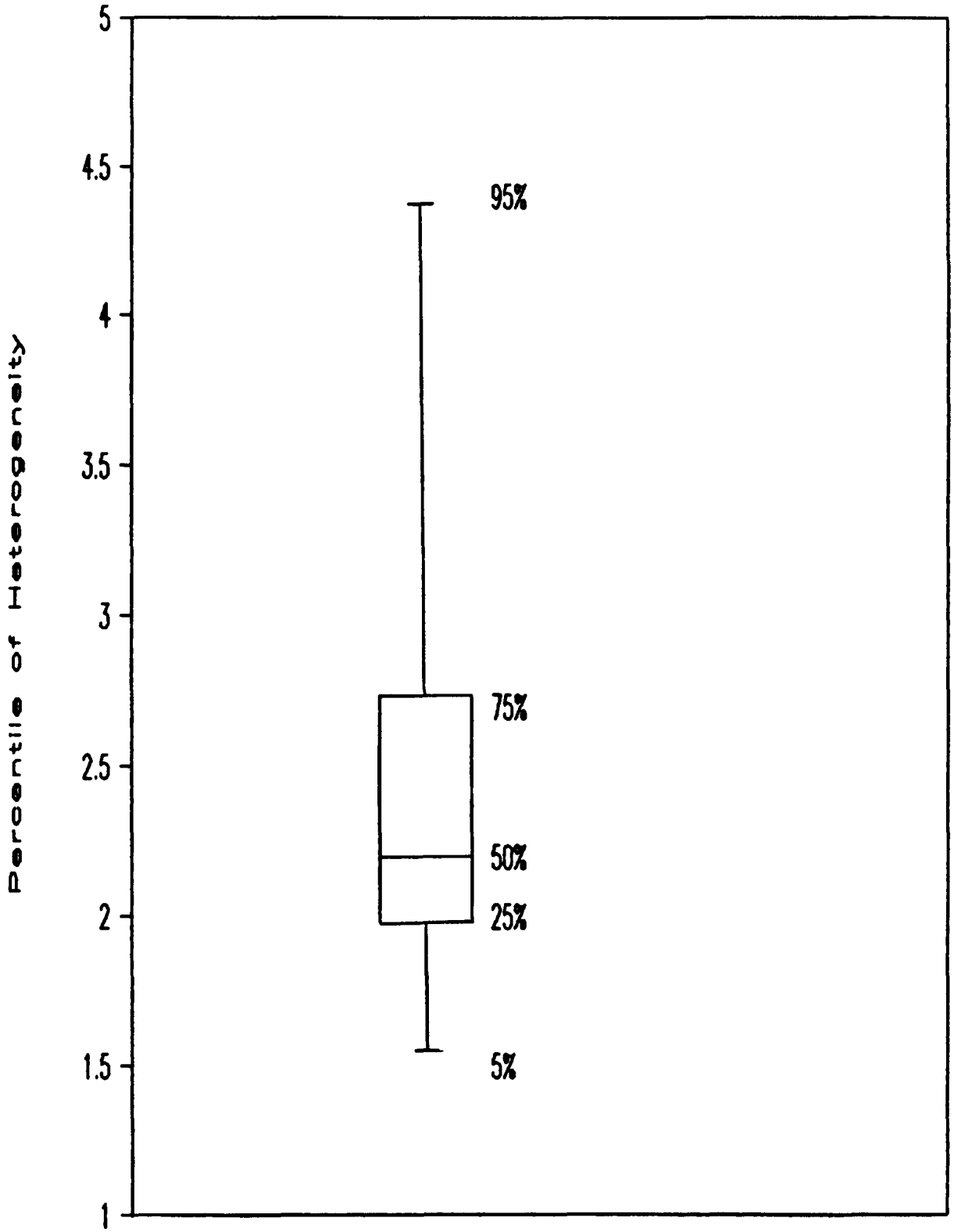

Figure 24. Box and Whiskers Plot of Heterogeneity

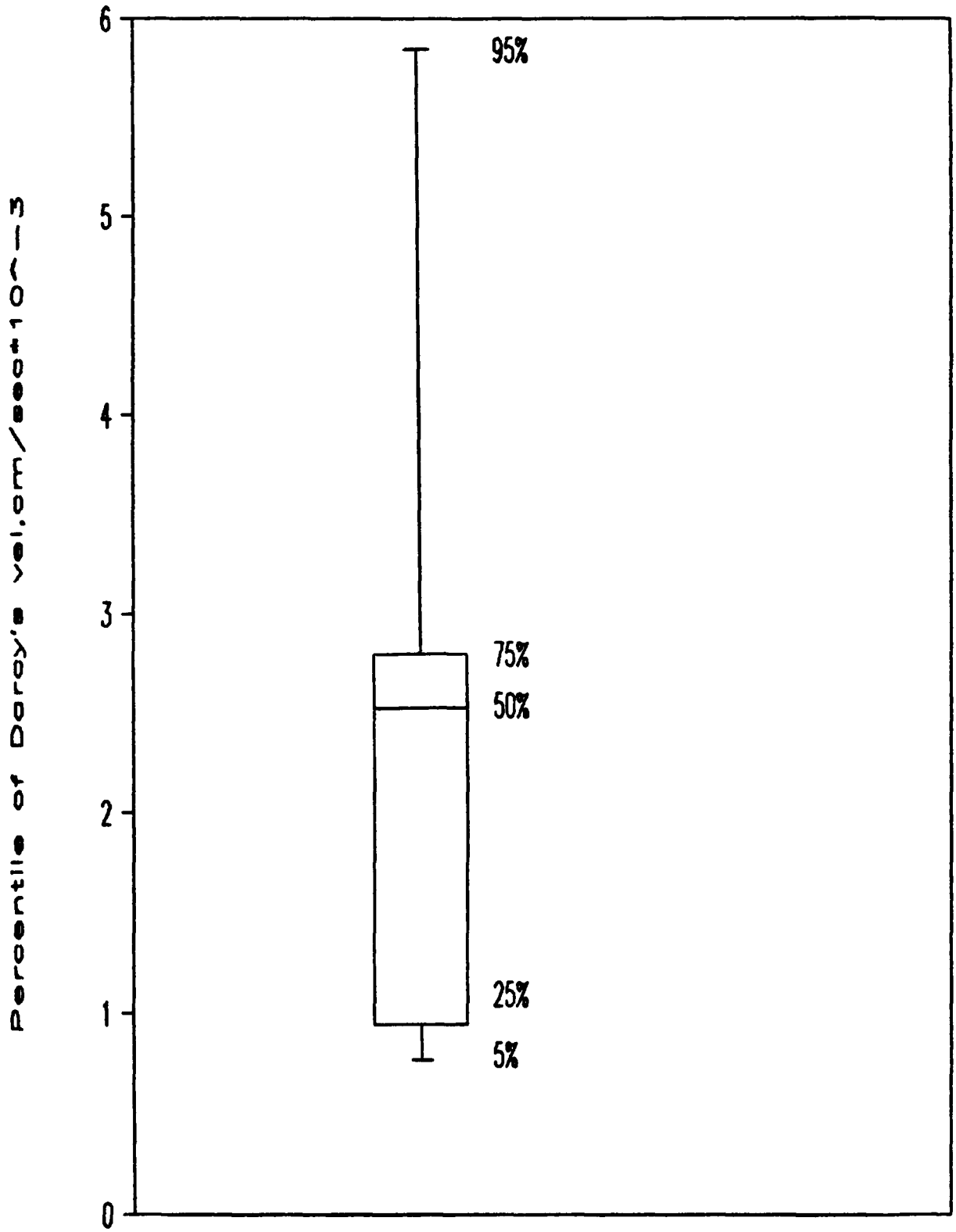

Figure 25. Box and Whiskers Plot of Darcy Velocity

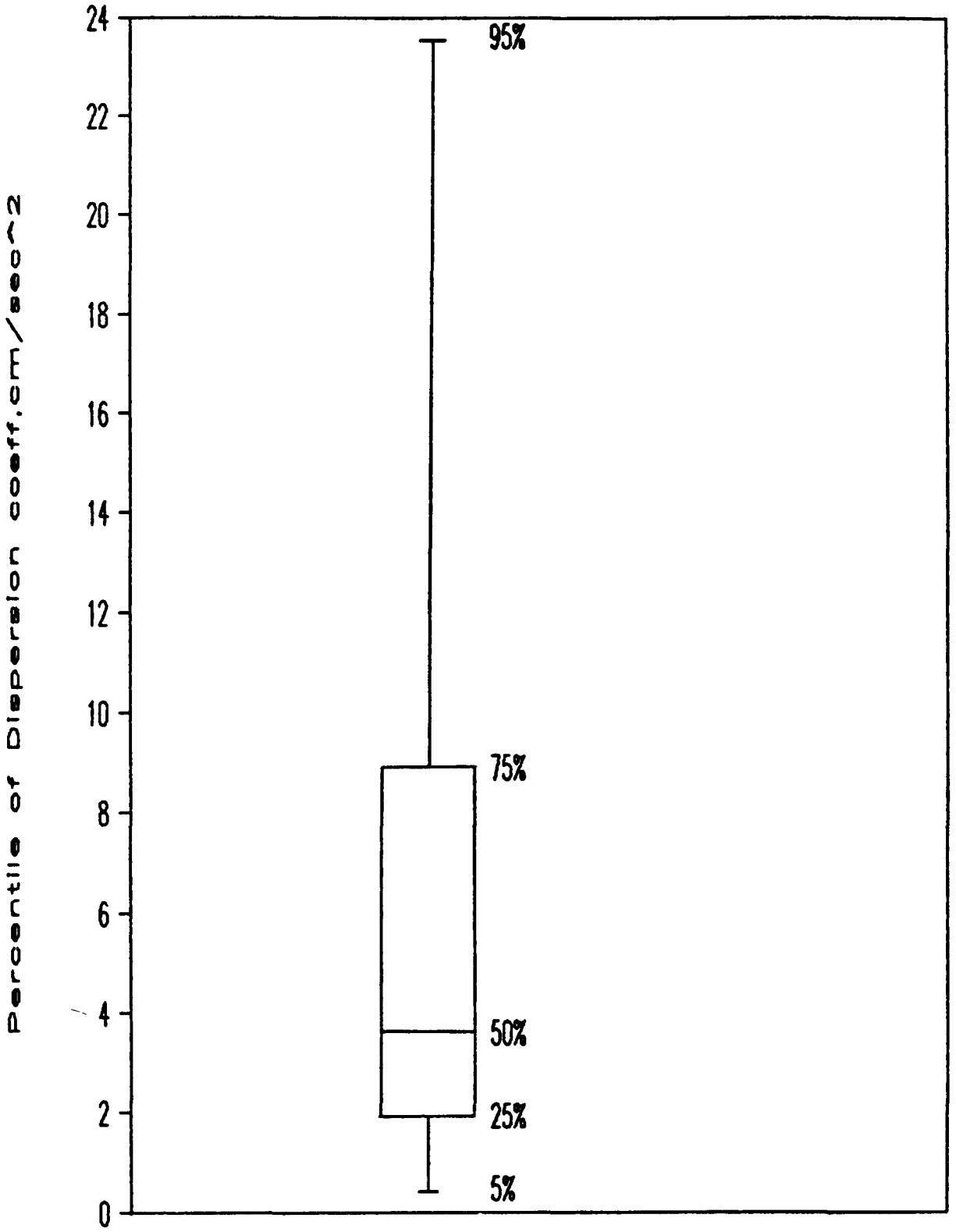

Figure 26. Box and Whiskers Plot of Dispersion Coefficient

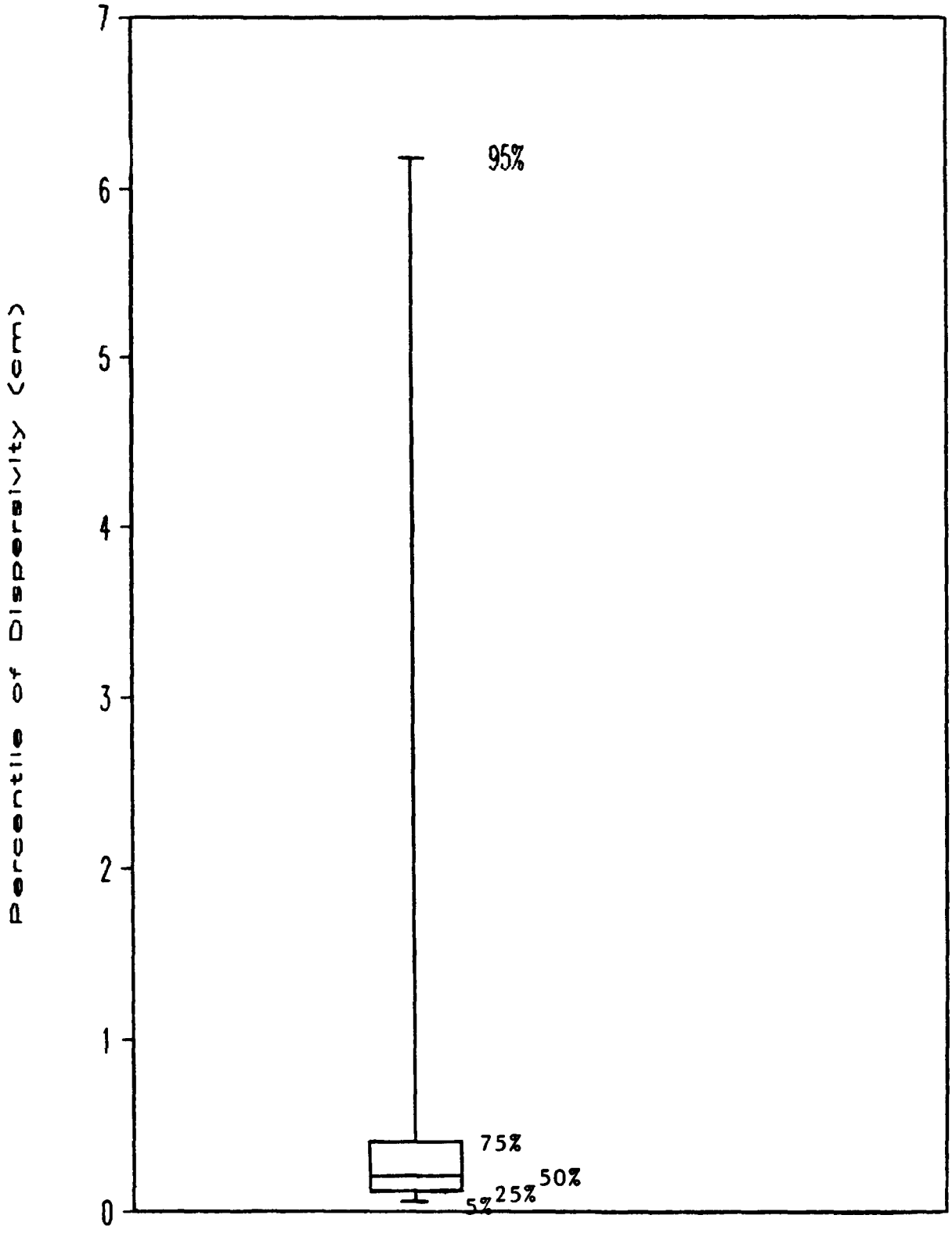

Figure 27. Box and Whiskers Plot of Dispersivity

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