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# A COMPARISON OF RELATIVE PERMEABILITY FROM CENTRIFUGING VERSUS COREFLOODING

SUPRI TR 72

By
David T. Shimbo

May 1990

Performed Under Contract No. FG19-87BC14126

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# ABSTRACT

Relative permeability and capillary pressure data from both centrifuge and coreflooding experiments on the same Berea sandstone will be analyzed using both analytical and simulation techniques. A linear two phase simulation model of fluid displacement from a core will be built. Capillary, gravity, and viscous effects will be included.

# 1. INTRODUCTION

Measurement of relative permeability from laboratory data has become an increasingly important subject in reservoir engineering as the need has arisen for more accurate forecasting of production and ultimate recovery. Engineers now recognize that the shape of the relative permeability curve is as important as the endpoint saturation.

Several methods of measuring relative permeability are available, but the Johnson, Bossler, and Naumann (JBN) unsteady state coreflood technique has predominated over other methods because of it's simplicity and relatively short experimental time. This method essentially floods a saturated core plug with a nonwetting fluid at a constant rate. Cumulative recoveries of the wetting and nonwetting phases versus time are measured at the outlet face. These recovery versus time relationships are converted to relative permeability curves using a graphical technique developed by Jones and Roszelle.

Relative permeability for the wetting phase can also be measured from centrifugal data using a method developed by Hagoort. An oil-saturated core is placed in a centrifuge with gas introduced at the inlet face. The centrifuge is rotated at a constant speed, and cumulative recovery vs. time is measured at the outlet face. This data is then converted to relative permeabilities using a log-log plot to determine Corey coefficients for the wetting phase.

The relative permeability curves from centrifuging and coreflooding often differ in both shape and endpoint saturations. Centrifuge curves cover a wider range of saturations and have a tendency to exhibit lower residual wetting phase saturations. Coreflood curves require extrapolation to residual saturation endpoints, and measurement error often results from the graphical determination of slope.

The objectives of this research are to:

1. Build a generalized coreflood/centrifuge model for determining relative permeability.

2. Compare laboratory relative permeability data from the same rock using the Jones and

Roszelle method for coreflooding versus the Hagoort method for centrifuging.

3. Use a simulation model, a least squares algorithm, and laboratory data to history match Corey parameters for both centrifuge relative permeabilities and coreflood relative permeabilities.

This problem was investigated from two different perspectives:

1). Experimental analysis of laboratory data - Coreflood and centrifuge relative permeability experiments on Berea sandstone samples were completed by Chevron Oilfield Research Company (COFRC). This data was processed using the Jones and Roszelle method for coreflooding and the Hagoort method for centrifuging. Relative permeability results were compared.

2). Simulation models - Linear coreflood and centrifuge simulation models were built that included terms for capillary pressure and centrifugal force. A least squares algorithm that adjusted the coefficients in the Corey equations was used to match experimental data with model data. The experimental relative permeability curves from coreflooding and centrifuging were compared with the history match relative permeability curves.

By comparing relative permeability curves from coreflooding versus centrifuging, the key parameters that influence the relative flow of oil, gas, and water through porous media are identified. This, in turn, will improve the application of raw laboratory relative permeability curves to large scale engineering problems.

## 2. LITERATURE REVIEW

This literature survey is divided into three sections: 1) capillary pressure, 2) relative permeability, and 3) simulation of coreflood and centrifuge displacement. A reference list at the end of this survey provides relevent papers for these topics.

### 2.1 Capillary Pressure

Capillary pressure was chosen as the initial subject for the literature survey because it provided a detailed microscopic and mechanistic perspective on fluid flow through porous media. A classic paper by Leverett in 1940 is the basis for most modern theory on capillary pressure. The most significant idea proposed was the concept of a characteristic distribution of interfacial two-fluid curvatures with water saturation. Three general occurrences of water in a porous solid were discussed: 1) a saturation region, 2) a pendular region, and 3) a funicular region. Experimental determination of the curvature/saturation relationship was described. The existence of an outlet face capillary pressure boundary effect was noted, and it's significant effect on small scale flow experiments was emphasized.

A more detailed paper on the mechanism of fluid flow through porous spaces was prepared by Mohanty in 1987. This paper reported on the physics of pore level events when water displaced oil in an initially oil-filled porous rock. These displacements were controlled by pressure distribution, capillary pressure, local pore geometry, pore topology, and PVT properties. A simple rock model, represented by a square network of pores, analyzed the physics of oil advancement and disconnection at the pore level. The capillary-controlled oil displacement processes of choke-off, jump, and oil-blob formation were described. The results gave insight into residual oil saturation and it's dependence on pore geometry and capillary number. As capillary number increased, the residual oil saturation decreased and oil blobs tended to be smaller. As pore size distribution became wider, the decrease of residual oil saturation with capillary number became smoother.

The standard experimental technique for the determination of capillary pressure from a centrifuge was developed by Hassler and Brunner in 1944. Their initial discussion focused on describing two older methods of determining capillary pressure (capillary diaphragm and gravity drainage) and discussing their shortcomings (too slow and inaccurate at high displacement pressures). The centrifuge apparatus and laboratory procedure were described in detail. The 100% saturated core was centrifuged at increasing rates and the average saturation was measured at each rate with a stroboscopic device. It was shown that accelerations and saturation values could be converted into a capillary pressure versus saturation plot. Final capillary pressures curves compared favorably for all three techniques. Strengths (speed, simplicity) and weaknesses (no hysteresis data, experimental inaccuracy) were noted.

Slobod and Chambers (1951) compared the centrifuge with other methods for determining capillary pressure. The primary advantages of the centrifuge were: 1) rapid establishment of equilibrium, 2) better precision and reproducible results, 3) availability of a high pressure difference between phases, 4) simple operational procedure; and 5) ability to complete experiments in one day or less.

Hoffman (1963) proposed a variation of the Hassler-Brunner method that was faster and provided an analytic method for the conversion of centrifuge data into capillary pressure data. The technique differed from the Hassler-Brunner method in that the centrifuge was slowly accelerated from zero to the maximum speed rather than being held at constant, progressively higher speeds. Both techniques were described in detail, and capillary pressure results from the same piece of core compared favorably. Shorter experimental time was an important advantage of the Hoffman technique over the Hassler-Brunner method. However, the Hoffman technique was not widely used because of experimental error in the dynamic measurement of recovery data, but it may have new applications with the introduction of more accurate centrifuges.

More recent articles on capillary pressure investigated the interrelationship between capillary forces, viscous forces, and saturations. New mathematical methods quantified these variables into functional groups with parameters that could be optimized for history matching.

Melrose and Brander (1974) described the macroscopic displacement process as a sudden and rapid pore-to-pore movement called rheons. This mechanism accounted for hysteresis in capillary pressure and relative permeability curves, and also justified the existence of residual (yet still mobile) saturations. This article is useful for describing the mechanistic factors which influence pore-to-pore movement. Their summary inevitably leads to the proper conclusions: reduce capillary forces, reduce residual oil saturations, and improve recovery.

Bentsen and Anli (1977) discussed parameter estimation techniques for the determination of capillary pressure from centrifuge data, and proposed a modification to the Hassler-Brunner technique that did not require numerical or graphical differentiation of experimental data. A mathematical model of capillary pressure was combined with a least squares estimation of non-linear parameters to match experimental data. After these nonlinear parameters were derived, the capillary pressure model was used to derive a smooth capillary pressure curve. When compared with the Hassler-Brunner graphical method, the capillary displacement pressures using the parameter estimation methods were considerably lower than the values that were obtained by extrapolating data from plots. Two explanations for this discrepancy were proposed: 1) measurement error; and 2) end effect boundary conditions resulting in a different saturation distribution at the outlet face.

The latest improvement in the measurement of capillary pressure is the result of a new, more accurate centrifuge designed especially for displacement tests. Firoozabadi, et al.(1986) prepared a paper on the measurement and simulation of capillary pressure using this centrifuge. The unique feature of this centrifuge was that the rock sample was always in contact with the wetting phase at the outlet face. The improved accuracy in measurement of expelled fluids gave higher quality experimental data, and the outlet face saturation condition made the centrifuge boundary condition more accurate. Their paper discussed the mechanism of gravity drainage and noted that its two primary components were relative permeability and capillary pressure. Basic equations used for deriving capillary pressure were presented. A nonlinear least squares statistical package was used to curve fit data and build a capillary pressure model that included terms for water saturation, interfacial tension, threshhold pressure, and centrifugal force.

## 2.2 Relative Permeability

Relative permeability is the basis for multiphase flow through porous media. The literature search concentrated on: 1) the mechanistic theory of fluid movement from pore-to-pore, 2) the derivation of flow equations and boundary conditions, and 3) the experimental procedure for measuring relative permeability from both the coreflood and the centrifuge.

The concept of relative permeability and its effect on the movement of gas, oil, and water through porous medium was first described by Buckley and Leverett (1942). They discussed the dynamics of oil displacement by either gas or water, and proposed the (at that time) new concept that water was a better displacement fluid than gas because of more favorable mobility ratios and less significant relative permeability reductions. Although they ignored capillary pressure effects in their calculations, they noted its importance in determining water/oil contacts at equilibrium and analyzing gravity drainage rates. The paper ended by recommending moderate production strategies in areas of potential coning so that relative permeability reduction from water influx would be minimized.

The Buckley-Leverett method was modified by Welge in 1952 when he derived an analytical method for computing average saturation. Darcy's Law was used for both wetting and non-wetting phases, and then combined with a material balance equation that resulted in equations describing saturation distributions in the core. With this method, the movement of the saturation front in a linear core could be tracked, and the average saturation behind the front could be calculated.

Corey (1954) presented a method for calculating oil relative permeabilities from measured gas permeabilities. The Kozeny-Carmen equation and the properties of the capillary pressure desaturation function were used to relate pore volume and tortuosity to capillary pressure. He compared measured data versus calculated data from 40 samples and found a good correlation with about two-thirds of the experiments. Experimental error was noted in cores with considerable amounts of dolomite or in cores with pronounced stratification. He proposed a relationship between capillary pressure and saturation:

$$\frac{1}{P_c} = C \frac{(S_o - S_{or})}{(1 - S_{or})} \tag{2.1}$$

$P_c$ = capillary pressure

$S_o$ = oil saturation

$S_{or}$ = residual oil saturation

$C$ = constant

He also proposed important expressions for gas/oil and oil/water relative permeabilities:

$$k_{ro} = \left[ \frac{(S_o - S_{or})}{(1 - S_{or})} \right]^4 \tag{2.2}$$

$$k_{rg} = \left[ 1 - \frac{(S_o - S_{or})}{(S_g - S_{or})} \right]^2 \left[ 1 - \left[ \frac{S_o - S_{or}}{1 - S_{or}} \right]^2 \right] \tag{2.3}$$

$k_{ro}$ = oil relative permeability

$k_{rg}$ = gas relative permeability

$S_g$ = gas saturation

Chierici (1984) proposed four- and five-parameter equations for gas/oil and oil/water relative permeability curves. He claimed that his relative permeability model reproduced initial points and end points more accurately than the Corey relationships.

$$\ln(k_{rog}) = -A \left[ \frac{S_g - S_{gc}}{1 - S_{wi} - S_g} \right]^L \tag{2.4}$$

$$\ln(k_{rg}) = -B \left[ \frac{1 - S_{wi} - S_g}{S_g - S_{gc}} \right]^M \tag{2.5}$$

$$\ln(k_{ro}) = -A\left[\frac{S_w - S_{wi}}{1 - S_{or} - S_w}\right]^L \tag{2.6}$$

$$\ln(k_{row}) = -B\left[\frac{1 - S_{or} - S_w}{S_w - S_{wi}}\right]^M \tag{2.7}$$

where: A, B, L, and M = positive empirical constants

$k_{rog}$ = relative permeability to oil (drainage)

$k_{rg}$ = relative permeability to gas (drainage)

$k_{ro}$ = relative permeability to oil (imbibition)

$k_{row}$ = relative permeability to water (imbibition)

$S_{wi}$ = irreducible water saturation

$S_{gc}$ = critical gas saturation

A paper that described factors which affected laboratory measurement of relative permeability was prepared by Osaba and Richardson (1951). Results of laboratory measurement of relative permeabilities on small core samples were presented using five different methods - Penn State, single core dynamic, gas drive, stationary liquid, and Hassler techniques. The influence of factors such as boundary effects, hysteresis, and injection rate were discussed. The most significant boundary effect influencing coreflooding was the capillary pressure effect at the outlet face of the core. Because of the capillary forces within the core, the rock tended to retain the wetting phase at the outlet face. This resulted in a higher water saturation at the outlet face. To minimize this boundary effect error, high rates of flow were recommended. To remove hysteresis effects, coreflooding in only one direction was recommended. The results indicated that all five methods yielded essentially the same relative permeabilities to gas. For oil/water relative permeabilities, the Hassler-Brunner method gave consistently lower residual oil saturations than other methods.

The classic paper on determination of relative permeability from experimental coreflood data was prepared by Johnson, Bossler, and Naumann (JBN) in 1958. It used the theory initially proposed by Buckley and Leverett (later modified by Welge) to calculate individual relative permeabilities. JBN theory made three important assumptions: 1) the flow velocity was the same at all cross sections of the linear porous body, 2) flow velocity was high enough to achieve Buckley-Leverett displacement, 3) capillary effects were negligible at high injection rates. To verify theoretical proposals, JBN relative permeability curves from small core plugs were compared with steady state relative permeability curves from whole cores. It was concluded that the JBN method was faster, required smaller core samples, and reproduced steady state coreflooding effectively.

Jones and Roszelle (1978) developed a graphical technique for determining relative permeability from unsteady state displacement experiments. A plot of average water saturation versus the reciprocal of pore volume injected was made. With this plot, the fractional flow of oil was equal to the inverse slope of the tangent line at any given saturation. Fractional flow was then converted to relative permeability using an effective viscosity plot. The Jones and Roszelle technique was used in this research to derive coreflood relative permeability curves.

Tao and Watson (1984) analyzed the JBN relative permeabilities by using a Monte Carlo technique to investigate the effects of different experimental operating conditions on the accuracy of relative permeability estimates. They found that different viscosity ratios and different flow rates did not significantly change the shape of the curves. They also analyzed the different algorithms used for curve fitting with the JBN method. Results show that the algorithms could be ranked in order of decreasing accuracy: 1) linear regression, 2) optimal spline, 3) fixed spline, 4) cubic least squares, and 5) quadratic interpolation. Linear regression was preferred by the author, although fixed spline techniques were simplest and relatively accurate.

Bentsen (1976) investigated scaling requirements during measurement of relative permeabilities and proposed several simplifying assumptions for determining boundary conditions and mobility ratios. He began by deriving the basic flow equations and converting them into dimensionless variables. He then proposed that the dimensionless function for $k_{rw}$, $k_{rnw}$, and capillary pressure were directly related to $S_w$, provided that the transition zone between the displacing and displaced phase was sufficiently small. This allowed him to normalize the relative permeability curves to $S_w$ end points of 0.0 and 1.0 . He also proposed a method for estimating the mobility ratio by using the average water saturation behind the displacement front.

Development of dimensionless functions for saturations and pressures, and optimization of these functions to match experimental data has been the most recent frontier in relative permeability analysis. Kerig and Watson (1987) presented a paper using a parameter estimation approach to estimate relative permeability curves from two-phase displacement data. Functional mathematical groups were chosen to represent relative permeability curve equations, and adjustable coefficients ($a_0$, $b_0$, $a_w$, $b_w$) were then used to least squares fit actual experimental data.

Kerig and Watson's equations are as follows:

$$k_{ro} = a_o \left[ \frac{(1 - S_{or} - S_w + E)}{(1 - S_{or} - S_{wi} + E)} \right]^{b_o} - a_o \left[ \frac{E}{(1 - S_{or} - S_{wi} + E)} \right]^{b_o} \tag{2.8}$$

$$k_{rw} = a_w \left[ \frac{(S_w - S_{wi} + E)}{(1 - S_{or} - S_{wi} + E)} \right]^{b_w} - a_w \left[ \frac{E}{(1 - S_{or} - S_{wi} + E)} \right]^{b_w} \tag{2.9}$$

$a_0, b_0, a_w, b_w$ = adjustable coefficients

E = empirical error function

The cubic spline function was chosen because it was the lowest order spline that yielded visual smoothness. The algorithm was used to solve two test cases that confirmed improved accuracy when compared with the Corey relationships. This method was useful for non-dimensionalizing relative permeability curves and solving unknown parameters/coefficients implicitly.

An important method for measuring oil relative permeability using centrifugal gas/oil displacement data from small cores was developed by Hagoort (1980). He derived the basic flow equations for a linear coreflood, then non-dimensionalized these equations to allow for curve fitting of experimental data. He concluded that relative permeability to oil is a critical factor in the gravity drainage process. A graphical technique for deriving the wetting phase coefficients for the Corey equation was presented. This methodology was used to determine the wetting phase relative permeability curves from experimental centrifuge data. Hagoort's assumptions included insignificant capillary pressure effects and large differences in mobilities between the wetting and nonwetting phases.

## 2.3 Simulation of Corefloods and Centrifuges

The final topic examined in this literature survey is a fairly recent development that began with the use of reservoir simulators to examine production history. Archer and Wong (1973) were the first to use a reservoir simulator to model laboratory coreflood tests. Their model used basic core properties (porosity, permeability, water saturation) and trial-and-error relative permeability curves to match coreflood production history. The three Corey coefficients were used as the matching parameters. A one-dimensional, two phase model was used with constant rate inlet face boundary conditions and constant atmospheric pressure outlet face boundary conditions. Uniform permeability, porosity, and saturation were assumed. Capillary pressure was also assumed to be equal to zero because of high injection rates.

Sigmund and McCaffery (1979) updated Archer and Wong's work by including terms for capillary pressure in the finite difference solution of the Buckley-Leverett two phase flow equations. Relative permeability curves were characterized by two parameters that reflected the shapes of the wetting and nonwetting curves. These parameters were used in a nonlinear least squares solution to match simulation data with laboratory data. Boundary conditions were the same as with Archer and Wong, but the capillary pressure function required that the minimum outlet face saturation be equal to the wetting phase saturation at zero capillary pressure. Results showed that the least squares history match method provided a good representation of laboratory data and that capillary forces could significantly effect pressure and recovery data, especially at low injection rates.

The parameter estimation technique and least squares minimization methodology were criticized by Chavant and Cohen (1980) as leading to large errors, especially near endpoints. Instead, they proposed a special discontinous finite elements method which separated relative permeability and capillary pressure curves into distinct linear unknowns. This gave great flexibility to the shape of these curves (especially at the endpoints), and a very accurate, but poorly conditioned solution. A gradient was calculated by applying an optimum control technique to the discretized solutions. This gradient was minimized until a satisfactory history match was obtained.

Watson and Kerig (1986) took the parameter estimation technique one step further. They claimed that the accuracy of the methods proposed by Archer/Wong and Sigmund/McCaffery depended not only on the matching of the two exponential Corey coefficients, but also on the actual definition of the saturation function being exponentiated. Two main sources of error were defined: 1) a bias error which was the result of the use of functional groups that were not representative of the true relative permeability/saturation relationship, and 2) variance error which was the result of experimental error. Both a variable saturation function and a variable exponent were used to match laboratory data and minimize this bias error.

The form of the Corey relationship usually used is:

$$k_{ri} = C_i \, S_i^{b_i} \tag{2.10}$$

i = wetting or nonwetting phase

$b_i$ = Corey exponent

$S_i$ = normalized saturation functional group $= \dfrac{S_i - S_{ir}}{1 - S_{ir}}$

$C_i$ = constant for wetting or nonwetting phase

Watson and Kerig modified this equation to give:

$$k_{ri} = a_i S_i^{b_i} \tag{2.11}$$

$b_i =$ Corey exponent

$S_i =$ saturation functional group

$a_i =$ variable for wetting or nonwetting phase

O'Meara and Crump (1985) built a centrifuge simulation model that calculated relative permeability simultaneously with capillary pressure. The model was one-dimensional and contained terms for variable centrifugal acceleration and nonwetting mobility. Darcy's Law with a term for centrifugal force was combined with material balance equations for the wetting and non-wetting phases. Capillary pressure and the total wetting and nonwetting superficial velocity were defined and included in the flow equations. The solution to these equations was carried out using a forward finite difference scheme. Boundary conditions assumed a vanishing capillary pressure at the outlet face, and zero velocity of the wetting phase at the inlet face. Saturation endpoint data was used only to estimate the capillary pressure and as a starting point for the history match. Corey's equations and the capillary pressure term were parameterized. History matching consisted of using a least squares technique to find the parameters which minimized the difference between simulated data and measured production data. The major advantage of this method was that the near-equilibrium $S_w$ vs. $P_c$ data and the transient cumulative recovery data were both used to solve the flow equations. This was a significant improvement over previous methods which only used final cumulative recovery as a match point. This research uses O'Meara and Crump's methodology to derive flow equations for the centrifuge model.

Firoozabadi and Aziz (1986) used an IMPES reservoir simulator to model centrifuge laboratory tests. Their model followed the methodology of Hagoort, but included terms for capillary pressure and mobility ratio. Corey's equations were broken into two functional groups (wetting and nonwetting) and three parameters (two exponents and the coefficient of the normalized saturation function for the nonwetting phase). A nonlinear, least squares approach was used to match production history. The equations used were:

$$k_{rw} = (S_w^*)^{n_1} \tag{2.12}$$

$$k_{rn} = k_{rnwc}\,(1 - S_w^*)^{n_2} \tag{2.13}$$

$$S_w^* = \frac{S_w - S_{wc}}{1 - S_{wc}} \tag{2.14}$$

$n_1$, $n_2$, $k_{rnwc}$ = variable coefficients to be optimized

$k_{rw}$ = wetting phase relative permeability

$k_{rn}$ = nonwetting phase relative permeability

Production data from a coarse-grained limestone core and a fine-grained dolomite core were analyzed using the new model. Non-unique but accurate history matches were found using both laboratory capillary pressure data and inappropriately low capillary pressure data. Modification of wetting phase Corey relative permeabilities at low wetting phase saturations was recommended to minimize endpoint cumulative recovery error. Chierici's five parameter model was also used with no significant improvement in the history match.

## 2.4 Summary

The first two parts of this literature survey reviewed the mechanism, theory, and experimental procedure for capillary pressure and relative permeability. It was found that the two processes are uniquely interrelated: every capillary pressure measurement is influenced by relative permeability, and every relative permeability measurement is influenced by capillary pressure. Early relative permeability experimental calculations such as the JBN method assumed zero capillary pressure effects because of high injection rates, but more recent literature suggests that capillary pressure effects cannot be ignored, particularly when using small core samples or low injection rates.

Two graphical techniques for determining relative permeability from experimental data were reviewed - Jones and Roszelle for unsteady state coreflooding and Hagoort for centrifuging.

Several coreflood simulation models with sophisticated history matching algorithms were discussed. Most models used some form of the Corey relative permeability relationships to history match production data. Firoozabadi and Aziz noted that a non-unique history match solution can be obtained using different relative permeability models or different combinations of relative permeability and capillary pressure curves. O'Meara and Crump built a centrifuge simulation model that accurately represented their experimental data.

## 3.1 Experimental Description

Experimental data was supplied by Chevron Oilfield Research Company (COFRC). Coreflooding and centrifuge displacement tests were performed using Berea sandstone cores. All tests were performed in the drainage mode with gas (nitrogen or air) displacing white oil or with depolarized kerosene displacing a glycerol/brine mixture. For each Berea core, the following experimental procedure was followed:

1). Air permeability and helium porosity were measured using the long core (4.5" by 1").

2). The core was saturated with the wetting phase, then an unsteady state drainage relative permeability test was performed.

3). The long core was cleaned and dried, then cut into four equal segments (1" by 1").

4). Air permeability and helium porosity were measured on each of these segments.

5). Each core was saturated with the wetting phase, then placed in a centrifuge for drainage capillary pressure measurement.

6). The core plugs were cleaned, then air permeability was measured.

7). The core plugs were saturated with the wetting phase. Transient wetting phase production was measured at several rotational speeds (1000, 2000, 3000, 4000 R.P.M.)

A summary of the data (Appendix E) indicates that two coreflood (gas/oil and oil/water) and eight centrifuge tests (six gas/oil and two oil/water) were run.

Centrifuge capillary tests were run on all samples. $P_c$ versus $S_w$ plots for the gas/oil system showed residual oil saturations ranging from 0.10 to 0.25. The water/oil system showed more consistent residual wetting phase saturations of about 0.10. Each of these capillary pressure curves was converted into a simple functional form using the relationship:

$$P_c = A \ln \left[ \frac{S_w - S_{wir}}{1 - S_{wir}} \right] + P_{th} \tag{3.1.1}$$

$P_c =$ capillary pressure (atm)

$P_{th} =$ entry pressure (atm)

$A =$ constant obtained from cubic spline fit of experimental data

The gas/oil coreflood test ran for about 80 minutes and displaced 6.0 cc. (0.48 pore volumes) of oil. The production versus pore volume injected plot (figure IA-1) showed consistent displacement data. Additional early time recovery data would have been useful for history matching.

The water/oil coreflood ran for about 8 hours and displaced 8.0 cc. of the wetting phase (0.666 pore volumes) with a total injected pore volume of about 40. Breakthrough took place at about 2.4 minutes. The production versus pore volume injected plot (figure IIA-1) showed slight inconsistency in early time.

Both gas/oil and oil/water centrifuge data was slightly irregular in early time, probably due to measurement error. Higher RPM runs resulted in residual saturations as low as $S_{wir} =$ 0.16 for the 3000 RPM gas/oil run and $S_{wir} =$ 0.13 for the 4000 RPM water/oil run.

Rotational speed versus time data was supplied for the centrifuge so that history matching could account for acceleration from zero to a stabilized RPM. This data was quite useful for history matching, since the amount of production during this initial acceleration period (50-60 seconds) was significant.

This experimental procedure provided the raw data necessary to calculate unsteady state coreflood relative permeability, centrifuge relative permeability, and capillary pressure from the same rock sample. Coreflood and centrifuge simulation models were used to history match the production data by using a least squares minimization technique to modify the coefficients in the Corey equations. This allowed comparison of Corey coefficients obtained from coreflooding and centrifuging. History match relative permeability curves were also compared with results obtained from the graphical techniques of Jones and Roszelle for coreflooding and

Hagoort for centrifuging.

## 3.2 Relative Permeability from Coreflooding (Jones-Roszelle)

The Jones-Roszelle graphical technique for determining relative permeability was a useful way to provide an initial guess for history matching and also to verify the final history match solution using a non-simulation technique. Two plots were necessary: 1) average nonwetting phase saturation ($S_{navg}$) versus pore volume injected ($PV_{inj}$), and 2) effective viscosity versus pore volume injected. Average nonwetting saturation was calculated using:

$$S_{navg} = \frac{N_p}{V_p} \tag{3.2.1}$$

$S_{navg}$ = average nonwetting phase saturation

$N_p$ = produced water ($cm^3$)

$V_p$ = total pore volume ($cm^3$)

$S_{navg}$ was plotted versus pore volume of oil injected on a Cartesian scale (figure 3.1). The saturations at the outlet face of the core were determined by drawing a series of tangents to the curve. The intercepts with the ordinate axis were the outlet face saturations. These outlet face saturations were converted to fractional flows, which were then converted to relative permeabilities.

Effective viscosity was determined from:

$$\lambda^{-1} = \mu_b \frac{\Delta p q_b}{\Delta p_b q} \tag{3.2.2}$$

$\lambda^{-1}$ = effective viscosity (cp)

$\mu_b$ = viscosity of fluid used to find absolute permeability (cp)

$\Delta p$ = pressure drop across core (psia)

$\Delta p_b$ = pressure drop when finding absolute permeability (psia)

$q$ = injection rate (cc/sec)

$q_b$ = injection rate used when finding absolute permeability (cc/sec)

A Cartesian plot of effective viscosity versus pore volume injected (figure 3.2) was prepared. Using the same tangent method as previously described for the $S_{navg}$ versus pore volume plot, a series of tangents to the average viscosity curve were extended to the axis. The intercepts with the ordinate axis were the outlet face effective viscosities ($\lambda_{eff}^{-1}$).

Fractional flow for the wetting and nonwetting phases was determined using:

$$f_w = \frac{S_{navg} - S_{nint}}{PV_{inj}} \tag{3.2.3}$$

$$f_n = 1 - f_w \tag{3.2.4}$$

$f_w$ = fractional flow for wetting phase

$f_n$ = fractional flow for nonwetting phase

$S_{wint}$ = outlet face wetting phase saturation

$PV_{inj}$ = pore volume injected

Point values for relative permeability were calculated from:

$$k_{rw} = \frac{f_w \mu_w}{\lambda_{eff}^{-1}} \tag{3.2.5}$$

$$k_{rn} = \frac{f_n \mu_n}{\lambda_{eff}^{-1}} \tag{3.2.6}$$

$k_{rw}$ = wetting phase relative permeability

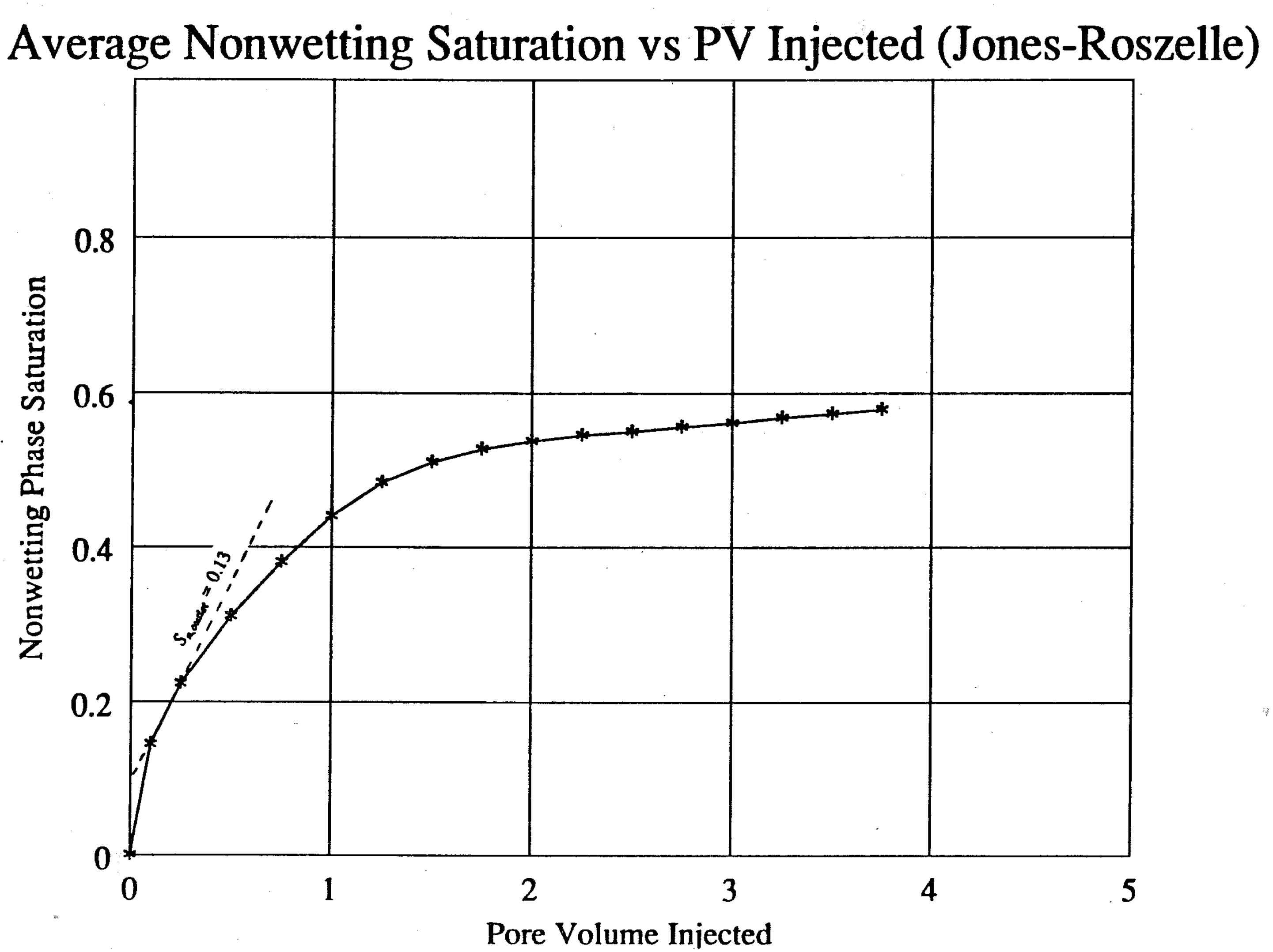
$k_{rn}$ = nonwetting phase relative permeability

$\mu_w$ = wetting phase viscosity (cp)

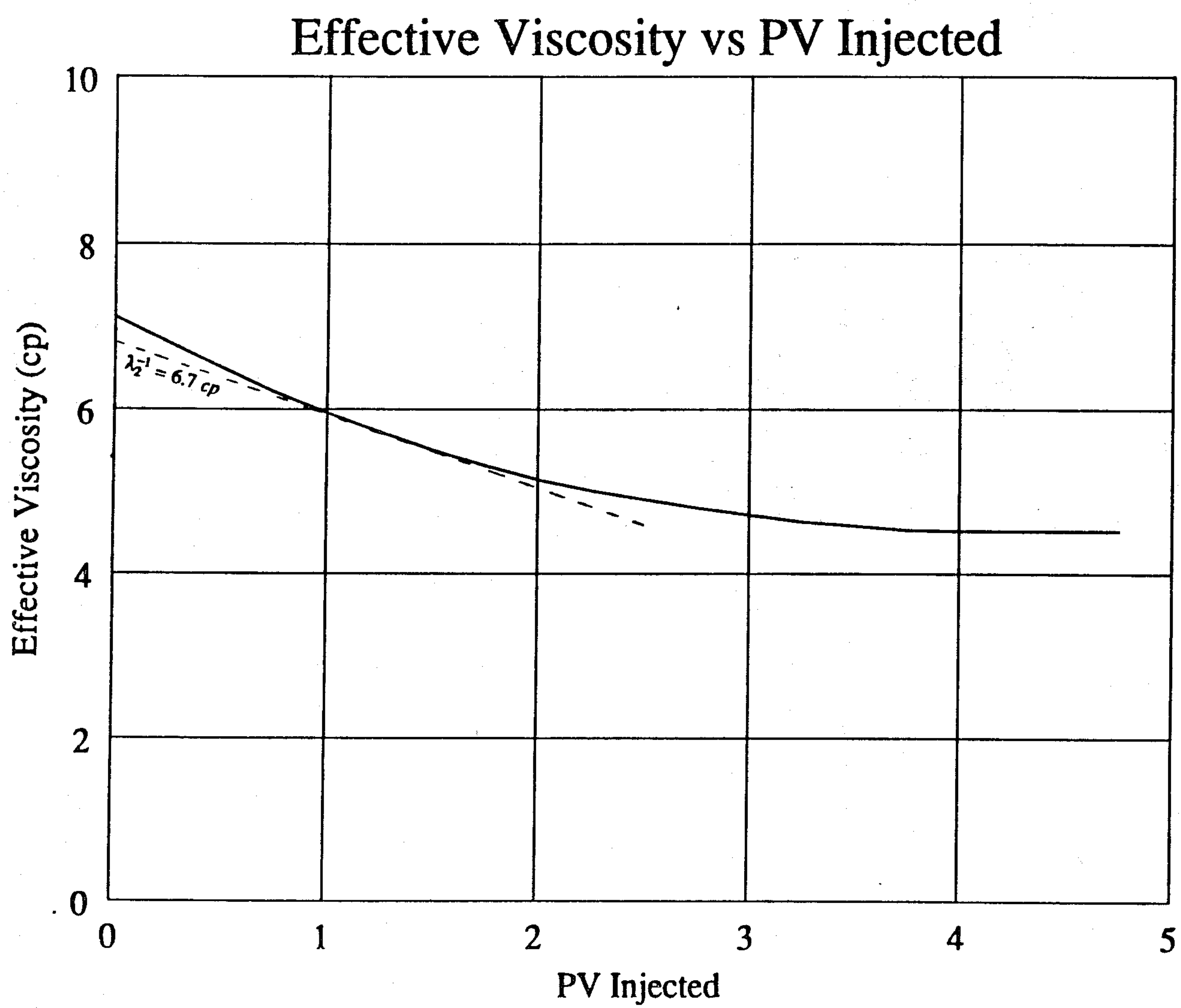
$\mu_n$ = nonwetting phase viscosity (cp)

$\lambda_{eff}^{-1}$ = outlet face effective viscosity

Values for the oil/water coreflood from the Berea sandstone are plotted in the Results and Discussion section (figure 5.1).




3.1 Water saturation vs. pore volume produced (Jones-Roszelle)




3.2 Effective viscosity versus pore volume produced

## 3.3 Relative Permeability from Centrifuging (Hagoort's Technique)

Hagoort derived a graphical technique for determining nonwetting phase relative permeability using the Corey relationship. He assumed an insignificant capillary pressure effect and a large mobility difference between gas and liquid phases.

Measurements during centrifuge displacement gave production versus time data. These were converted to dimensionless values:

$$N_p = \frac{cumulative\ production}{\phi^* A L} \tag{3.3.1}$$

$$t_d = \frac{\Delta\rho_{og} g k t}{\mu_o \phi^* L} \tag{3.3.2}$$

$$\phi^* = \phi\,(1 - S_{wir} - S_{or}) \tag{3.3.3}$$

$N_p$ = pore volume produced

$t_d$ = dimensionless time

$\phi^*$ = reduced porosity

$S_o$ = oil saturation

$S_{wir}$ = irreducible water saturation

$S_{or}$ = residual oil saturation

$\Delta\rho_{og}$ = density difference between oil and gas phases (g/cc)

$g$ = gravitational factor $= 4\pi^2 f^2 r_m$

$f$ = rotational frequency (cycles/min)

$r_m$ = length of rotational axis (cm)

$k$ = permeability (Darcys)

$\mu_o$ = viscosity of oil (cp)

$A$ = cross sectional area ($cm^2$)

$L$ = length of coreplug (cm)

$t$ = time (sec)

A plot of $\ln(1 - N_p)$ versus $\ln(t_d)$ was used to determine coefficients for a modified form of the Corey equation:

$$k_{rw} = k_{r0}^{0}\left[\frac{S_o - S_{or}}{1 - S_{or} - S_{wir}}\right]^{n} \tag{3.3.4}$$

$k_{r0}^{0} =$ wetting phase factor

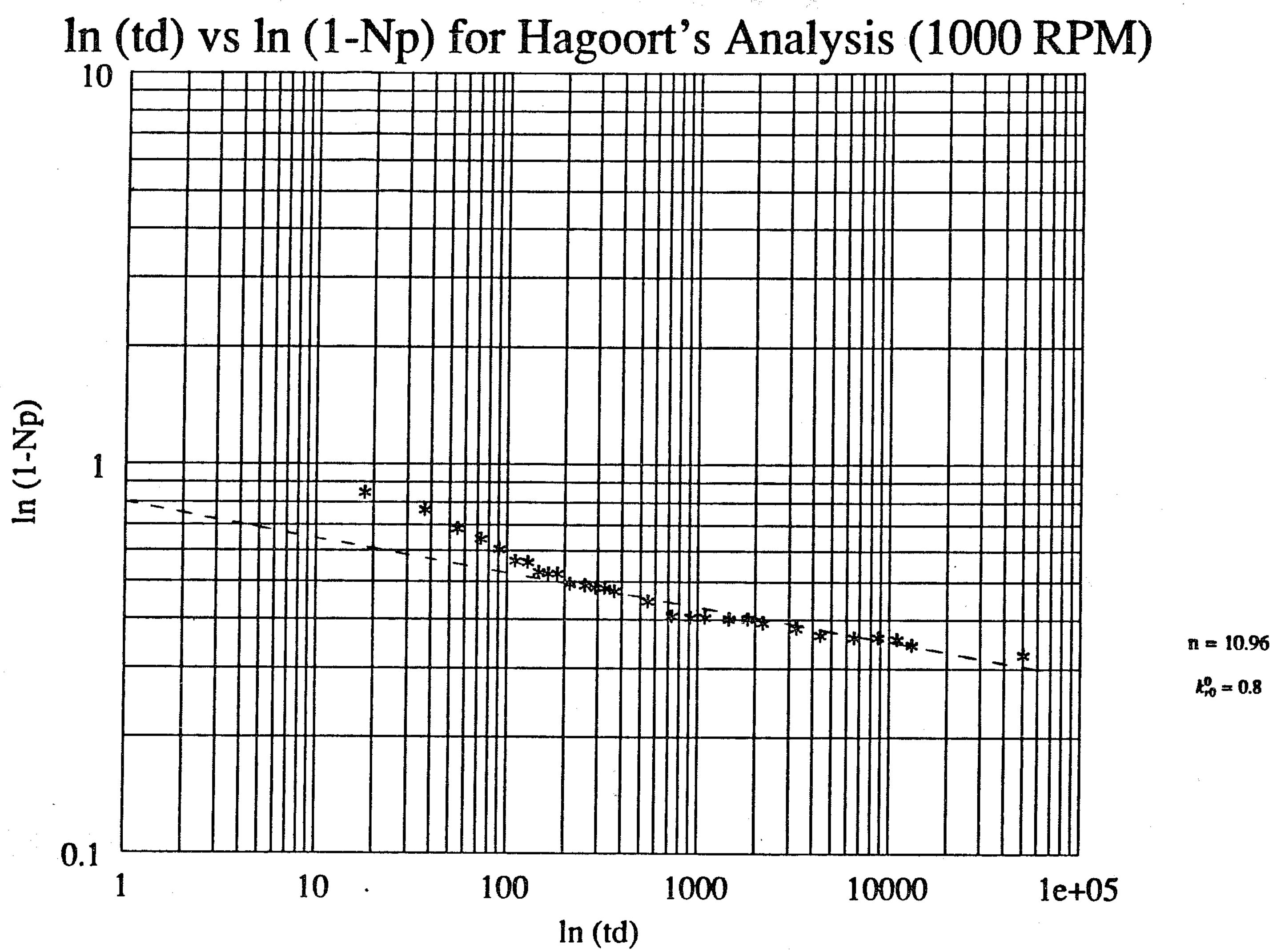
$n =$ wetting phase exponent

The exponential coefficient n was determined from the slope of the resulting straight line using the relationship:

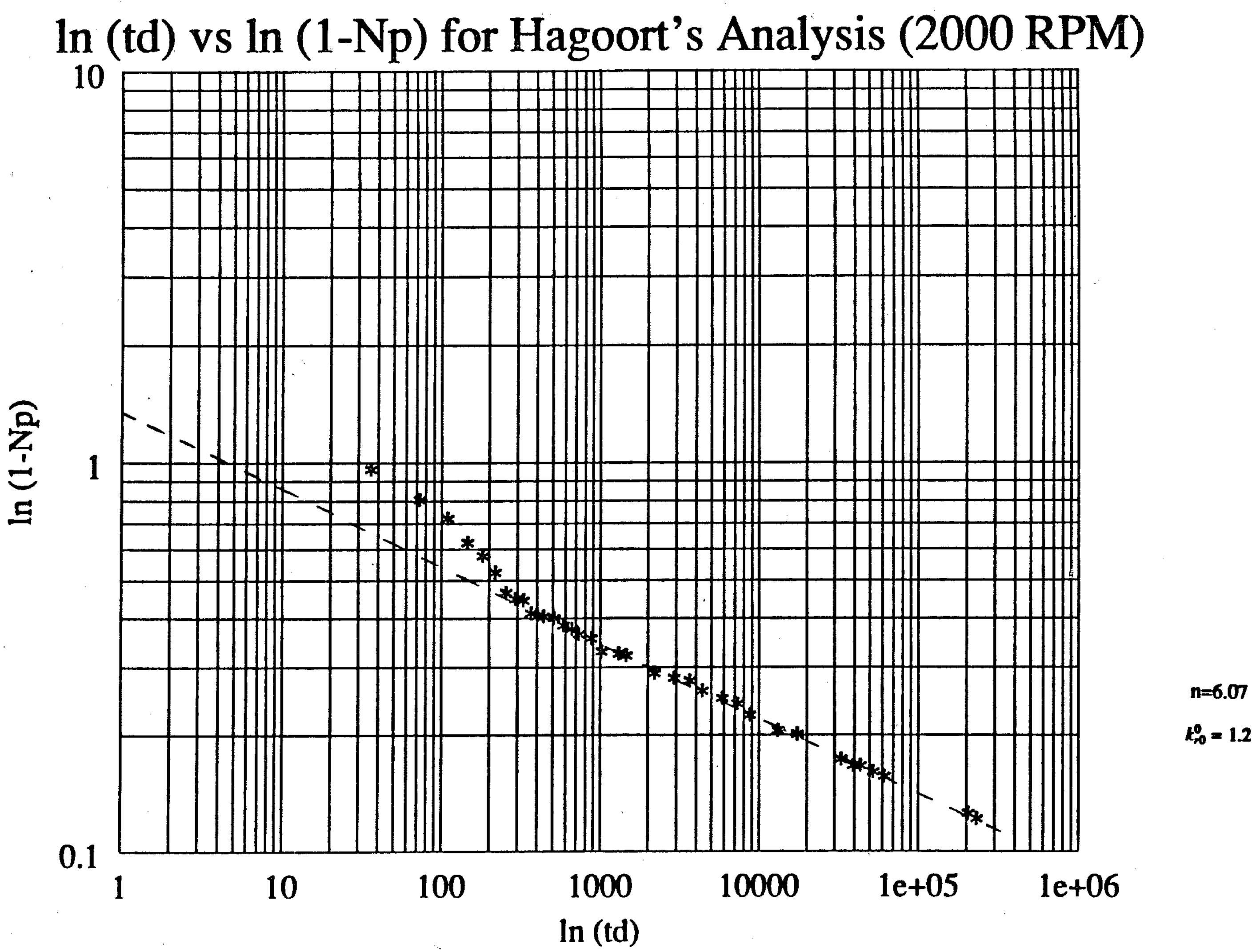
$$slope = \frac{d\ln(1 - N_p)}{d\ln(t_d)} = -\frac{1}{n - 1} \tag{3.3.5}$$

The factor $k_{r0}^{0}$ was obtained from the intercept of $t_d = 1$. Hagoort noted that $k_{r0}^{0}$ is a dimensionless curve fitting parameter and does not have any significance with respect to the endpoint of the oil relative permeability curve.

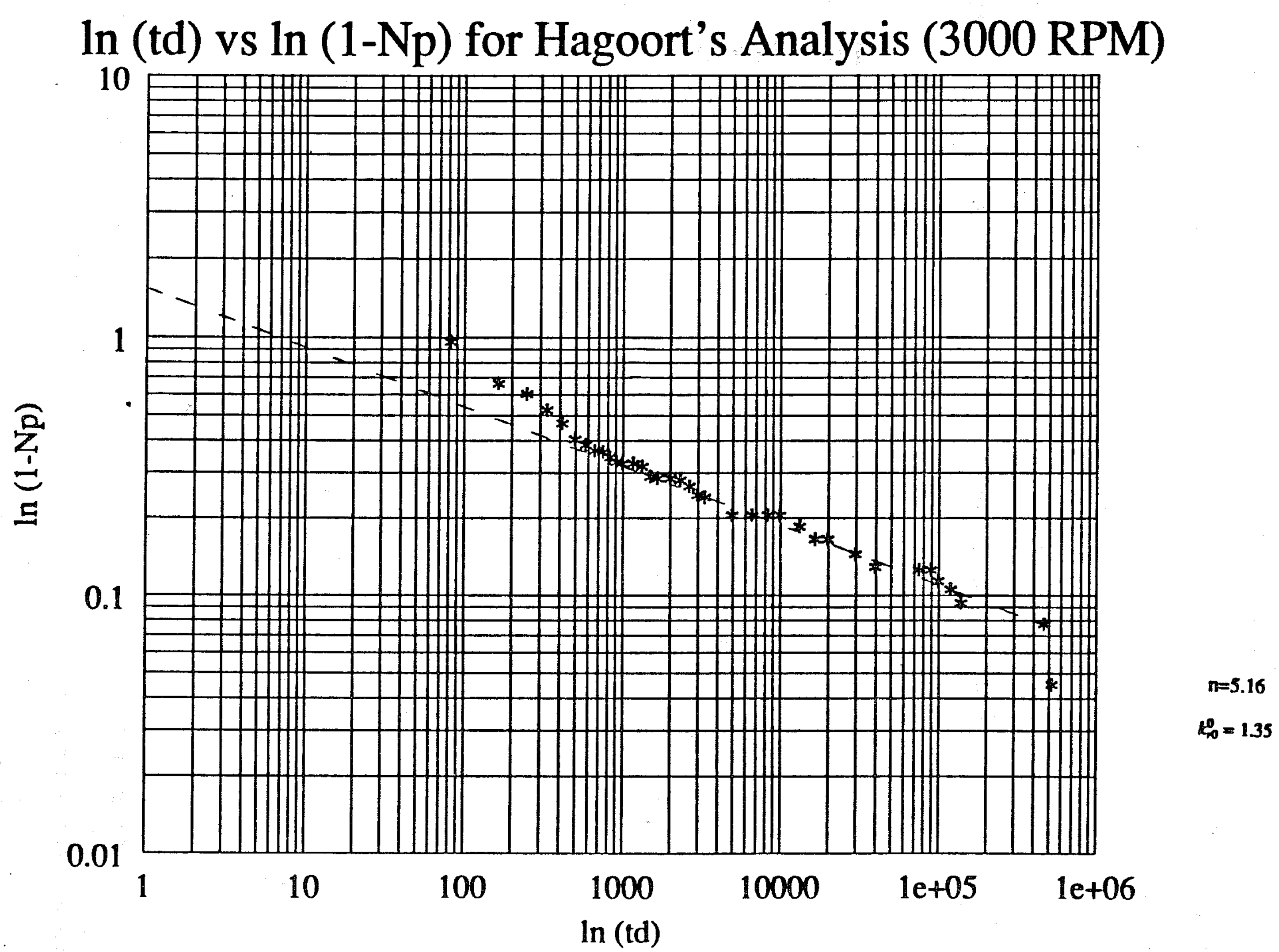
Experimental data for the 1000, 2000, and 3000 RPM gas/oil centrifuge systems are plotted in figures 3.3, 3.4, and 3.5. Two distinct slopes occur. The first slope represents the acceleration period from startup to constant R.P.M.. The second slope represents centrifugal displacement under constant acceleration, and is used to determine the Corey coefficients.




3.3 Hagoort $ln(1 - N_p)$ versus ln $t_d$ for 1000 RPM




3.4 Hagoort $ln(1 - N_p)$ versus ln $t_d$ for 2000 RPM




3.5 Hagoort $ln(1 - N_p)$ versus ln $t_d$ for 3000 RPM

## 4.1 Centrifuge Model Description

The centrifuge model is a linear one-dimensional multicell model that simulates a nonwetting phase displacing a wetting phase (drainage mechanism) in a coreplug under centrifugal acceleration. A 1" by 1" coreplug initially 100% saturated with the wetting phase is accelerated from 0 to 3000 RPM, then centrifuged at a constant RPM until recovery of the wetting phase is insignificant. Accurate measurements of centrifuge speed, recovery, and time are important throughout the run since shape and endpoints of the relative permeability curves are quite sensitive to these parameters. High permeability samples are quite sensitive to the initial acceleration period because a significant pore volume is displaced before the centrifuge reaches a stabilized rotational speed.

Important assumptions in the derivation of flow equations for the centrifuge include:

1). An incompressible rock system

2). Homogeneous porosity and permeability

3). Incompressible fluids

4). Linear Darcy flow

5). Two phases - wetting and nonwetting

An approach similar to the one described by O'Meara and Crump is used to derive the two phase flow equations. A detailed derivation can be found in Appendix A.

The centrifuge model consisted of 40 cells with intercell flow controlled by Darcy's law and an additional term for centrifugal acceleration. This modified form of Darcy's law was combined with the continuity equations to solve for saturation. The saturation solution was discretized, then solved explicitly. To maintain model stability, timestep size was automatically reduced if the saturation change in any cell exceeded 5%. A material balance check was also included to monitor solution error.

Flow of the wetting and nonwetting phases takes place according to relative permeability and fractional flow equations using the Corey relationships.

$$k_{rw} = \left[\frac{S_w - S_{wir}}{1 - S_{wir}}\right]^{C1} \qquad (4.1.9)$$

$$k_{rn} = C3\left[1 - \frac{S_w - S_{wir}}{1 - S_{wir}}\right]^{C2} \qquad (4.1.10)$$

$k_{rn}$ = nonwetting phase relative permeability

$k_{rw}$ = wetting phase relative permeability

C1, C2, C3 = Corey constants used in history matching experimental data

$S_w$ = water saturation

$S_{wir}$ = irreducible water saturation

Capillary pressure effects were also included in both centrifuging and coreflooding models. Experimental capillary pressure data from the rock samples was curve fit using a non-linear regression program and defined using the simple exponential relationship:

$$P_c = A \ln\left[\frac{S_w - S_{wir}}{1 - S_{wir}}\right] + P_{th} \qquad (4.1.10)$$

$P_c$ = Capillary pressure (atm)

A = Capillary pressure factor

$P_{th}$ = Entry/threshhold pressure (atm)

Boundary Conditions for the Centrifuge

Centrifuging is performed under a drainage mode, so the core is initially 100% saturated with the wetting phase, then displaced by the nonwetting phase using centrifugal force. Therefore, since only the nonwetting phase is entering the coreplug, the velocity of the wetting phase at the inlet face is zero.

$$u_{w,inlet} = 0 \qquad (4.1.11)$$

At the outlet face, several important assumptions are made. Since no production of the nonwetting phase takes place in centrifuging, it is proposed that the outlet face is 100% saturated with the wetting phase. The nonwetting phase displaces the wetting phase throughout the core except at the outlet face, which remains 100% wetting phase saturated. Within the core, the wetting phase saturation gradually decreases until only the irreducible saturation remains. This leads to the conclusion that capillary pressure is zero at the outlet face (see Appendix A for more detailed discussion).

$$S_{w,outlet} = 1.0 \tag{4.1.12}$$

$$P_{c,outlet} = 0.0 \tag{4.1.13}$$

It should be noted that this model is accurate for oil/water displacement, but may not be representative for gas/oil systems because of the assumption of incompressible fluids.

## 4.2 Coreflood Model Description

Coreflood model equations were defined using the same methodology and assumptions as the centrifuge derivation, except that the term for centrifugal acceleration was excluded from Darcy's law. This derivation can be found in Appendix B.

A 40 cell linear system was used to simulate the 1" by 1" coreplug. To verify the model, saturation profiles at various times were generated and compared with Buckley-Leverett calculations (figure 4.1). Breakthrough from the Buckley-Leverett $f_w$ versus $S_w$ plot (figure 4.2) was $S_{w,breakthrough} = 0.76$ while the model showed initial breakthrough at $S_{w,breakthrough} = 0.72$.

Additionally, a commercial simulator (black oil BOAST) was run using similar input data. Figure 4.4 compares the saturation profiles at two different pore volumes. Although breakthrough times were the same for both models, the saturation profiles are different because the BOAST model is more implicit and automatically adjusts timestep size. Numerical dispersion was much less in the explicit model than it was in the IMPES BOAST model.

### Boundary Conditions for Coreflooding

Initial conditions for coreflooding under a drainage mode assumed the 100% wetting phase saturated core being displaced by the nonwetting phase at a constant injection rate.

$$S_{w,initial} = 1.0 \qquad (4.2.1)$$

$$q_{inj} = constant \qquad (4.2.2)$$

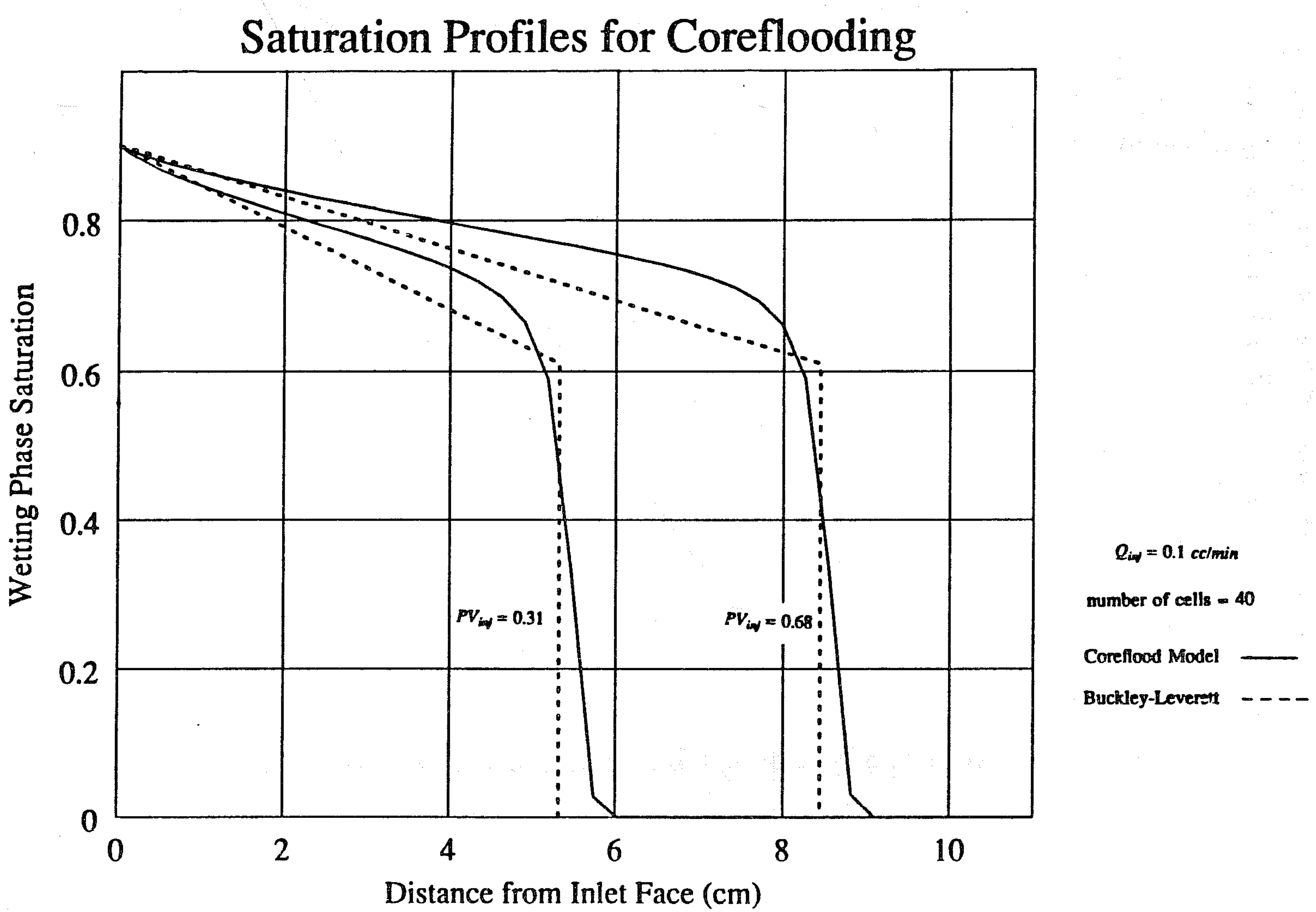
Before breakthrough assuming an incompressible fluid, the nonwetting phase injection rate at the inlet face equals the wetting phase production rate at the outlet face.

$$u_{nw}(x=0,t) = u_w(x=L,t) \qquad (4.2.3)$$

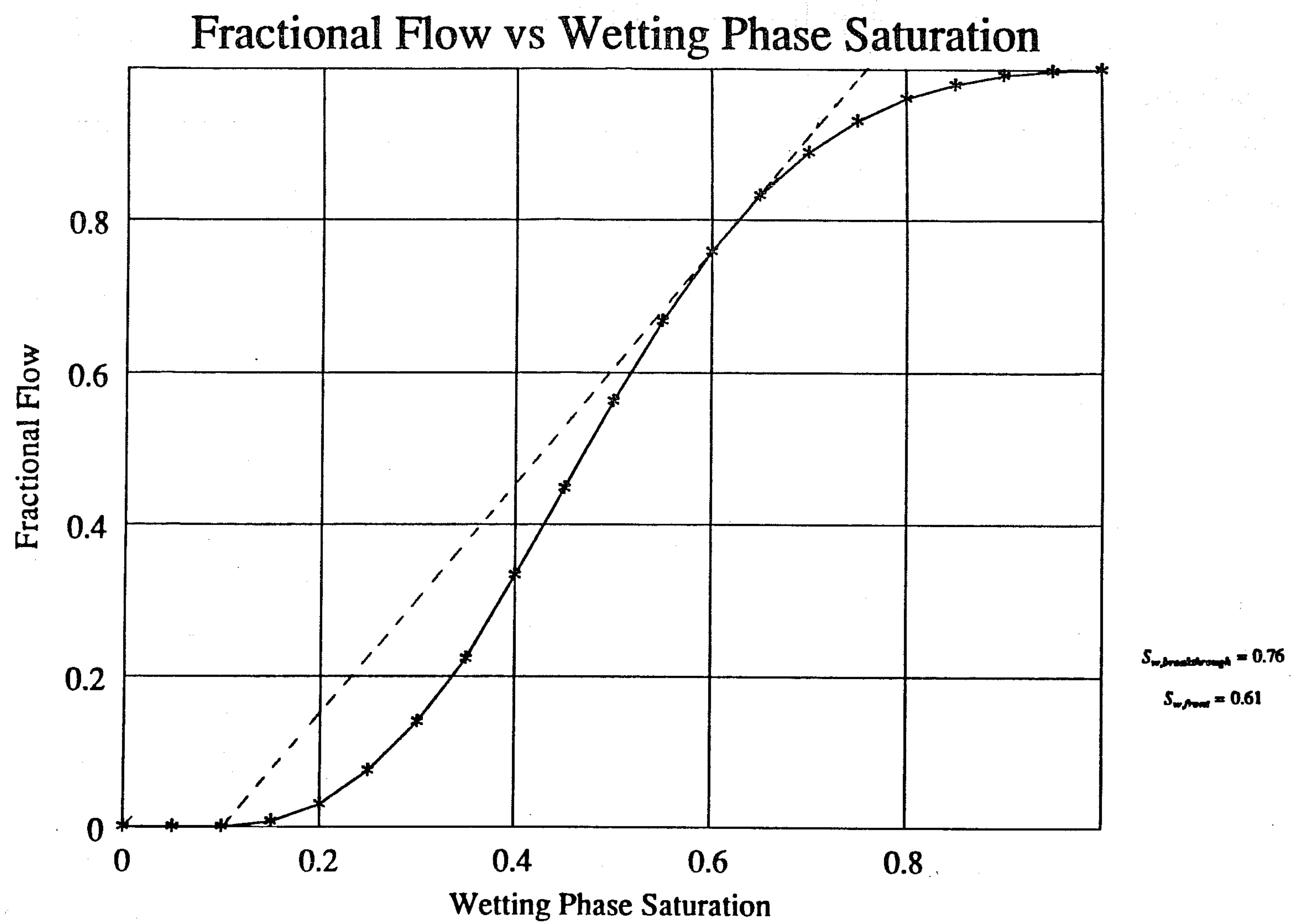
After breakthrough, the nonwetting phase injection rate at the inlet face equals the wetting phase production rate plus the nonwetting phase production rate at the outlet face.

$$u_{nw}(x=0,t) = u_{nw}(x=L,t) + u_w(x=l,t) \tag{4.2.4}$$

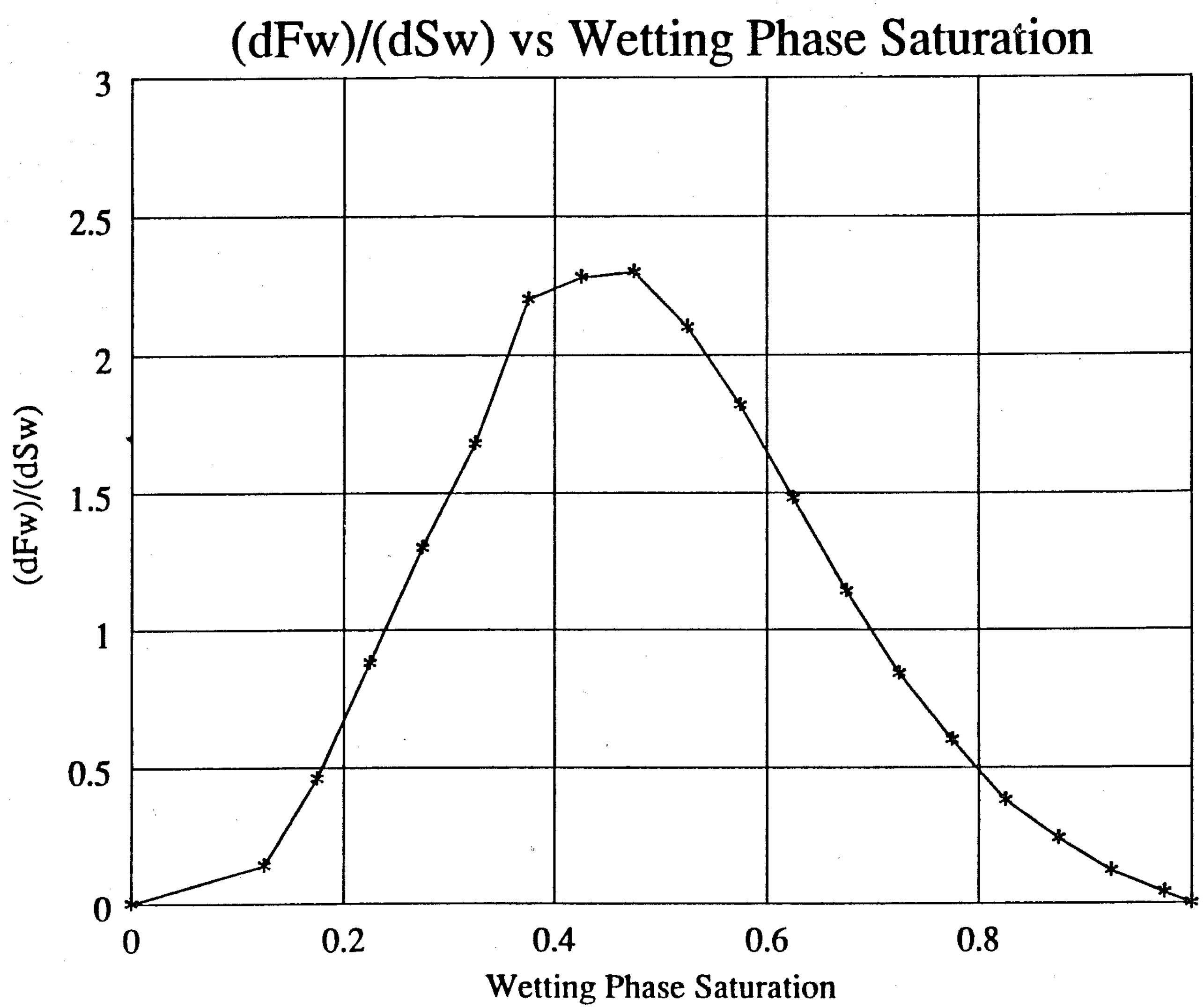
The outlet face of the coreflood allows production of both the wetting and nonwetting phases according to Corey relative permeability and fractional flow relationships.



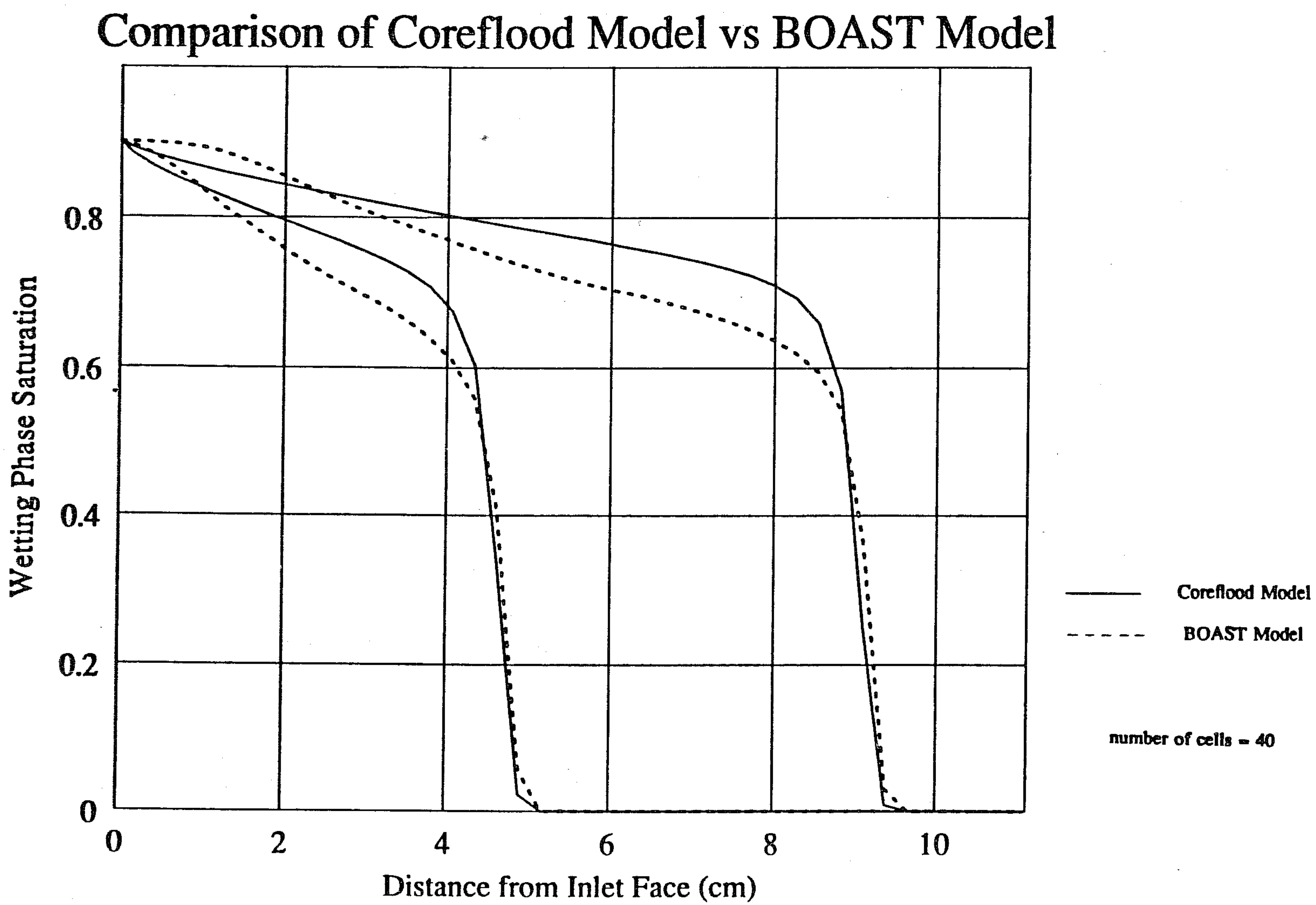

4.1 Saturation profiles for coreflooding




4.2 Fractional flow versus wetting phase saturation




4.3 $(dF_w\ /dS_w)$ versus wetting phase saturation (Buckley-Leverett)




4.4 Comparison of coreflood model versus BOAST model

## 4.3 Least Squares History Matching

The Corey relative permeability relationships were used to obtain an accurate history match of production data. The functional form consisted of three coefficients and two parameter groups for the wetting and nonwetting phases.

$$k_{rw} = \left[\frac{S_w - S_{wir}}{1 - S_{wir}}\right]^{C1} \tag{4.3.1}$$

$$k_{rn} = C3\left[1 - \frac{S_w - S_{wir}}{1 - S_{wir}}\right]^{C2} \tag{4.3.2}$$

$k_{rw}$ = wetting phase relative permeability

$k_{rn}$ = nonwetting phase relative permeability

$S_w$ = wetting phase saturation

$S_{wir}$ = irreducible wetting phase saturation

$C1$ = exponential factor for wetting phase

$C2$ = exponential factor for nonwetting phase

$C3$ = factor for nonwetting phase

A least squares history matching algorithm similar to the Firoozabadi and Aziz methodology was used to identify the optimal Corey coefficients that would best match experimental production data. The solution for the Corey coefficients was obtained by minimizing the least squares error defined by:

$$E = \sum_{j=1}^{m} w_j \left[R_j^{obs} - R_j^{calc}\right]^2 \tag{4.3.3}$$

$E$ = sum of the difference between observed and calculated recoveries

$w_j$ = weighting factor at time j

$R_j^{obs}$ = observed recovery at time j

$R_j^{calc}$ = calculated recovery at time j

$C_x$ = Corey coefficients C1, C2, C3

$m =$ number of history match points

The derivative of this error was taken with respect to each Corey coefficient:

$$\frac{\partial E}{\partial C_x} = \frac{\partial}{\partial C_x}\sum_{j=1}^{x} w_j \left[R_j^{obs} - R_j^{calc}\right]^2 = 0 \qquad x = 1, 2, 3 \tag{4.3.4}$$

A first order expansion of $R_j^{calc}$ resulted in a 3x3 matrix which was solved using Cramer's rule. A detailed description of this least squares minimization procedure can be found in Appendix C.

The methodology for history matching consisted of calculating an initial guess for each of the three Corey coefficients using the Jones-Roszelle or Hagoort graphical techniques. The irreducible water saturation ($S_{wir}$) was obtained from capillary pressure curve endpoints from each coreplug. Capillary pressure curves were input into the model using Equation 3.1.1.

Each iteration of the history match consisted of four separate model runs: 1) an initial base case run for C1, C2, and C3, 2) an increment of C1, 3) an increment of C2; 4) an increment of C3. Differences between the initial guess and incremental runs were calculated, and then compared with the difference between the initial guess and actual experimental data. Derivatives were calculated and substituted into the 3X3 matrix. The resultant solution to the matrix provided new incrementing values for the Corey coefficients. If each of the incrementing values was within a given tolerance limit ($10^{-2}$PV), then the history match run was concluded. If any of the coefficients was greater than the tolerance limit, then a new iteration would begin with updated Corey coefficients.

Another analytical approach for determining the derivative of calculated recoveries $\left[\frac{\partial R_i}{\partial C_x}\right]$ in equation 4.3.4 can be obtained by calculating $\left[\frac{\partial S_w}{\partial C_x}\right]$ in the explicit numerical model. Knowing the change in saturation with respect to the change in the Corey coefficient, the change in recovery can be calculated for each incremented coefficient. Using this method, the model only needs to be run once for each iteration, since the derivatives for C1, C2, and C3 can be explicitly calculated.

# 5. RESULTS AND DISCUSSION

This section is separated into four different parts. First, the graphical analysis of coreflood and centrifuge data will be reviewed. Secondly, simulation model behavior and sensitivities to timestep length, cell size, and capillary pressure will be discussed. Thirdly, relative permeability curves derived from Hagoort's and Jones-Roszelle techniques will be compared with relative permeability curves obtained from history matching. And finally, coreflood relative permeability curves will be compared with centrifuge relative permeability curves.

## 5.1 Results from the Jones-Roszelle and Hagoort Techniques

The Jones-Roszelle graphical technique was used to analyze the oil/water coreflood data (figure 5.1). The curves were skewed toward higher water saturations with the nonwetting phase having higher relative permeabilities than the wetting phase. This could be due to the large variation in viscosity between the wetting phase (7.12 cp) and the nonwetting phase (1.5 cp). A plot of average nonwetting phase saturation versus $1/PV_{inj}$ (figure 5.2) extrapolated to $\frac{1}{PV_{inj}} = 0$ indicated an irreducible wetting phase saturation of about 32% which is considerably higher than the capillary pressure measurement $S_{wir} = 10\%$. A longer coreflood run or higher injection rates may be necessary to obtain a more accurate $S_{wir}$.

Gas/Oil Corey Coefficients from Hagoort's Technique

| Sample | Centrifuge Speed (RPM) | n | $k^0_{rw}$ | $S_{wir}$ |
|---|---|---|---|---|
| BA-1A | 1000 | 10.96 | 0.80 | 0.10 |
| BA-1A | 2000 | 6.07 | 1.2 | 0.10 |
| BA-1A | 3000 | 5.16 | 1.3 | 0.10 |

Experimental data from the centrifuge for the gas/oil system was processed using Hagoort's graphical technique. This methodology supplies a wetting phase exponent (n) similar to the wetting phase Corey exponent (C1), and also an additional wetting phase factor ($k^0_{rw}$).

$$k_{rw} = k_{rw}^{0}\left[\frac{S_w - S_{wir}}{1 - S_{wir}}\right]^n \tag{5.1}$$

The residual wetting phase saturation ($S_{wir}$) was obtained from capillary pressure measurements and was consistently in the range of 0.09 - 0.13. Centrifuge production data from the gas/oil system was obtained at 1000, 2000, and 3000 RPM. Plots of $\ln(1 - N_p)$ versus $\ln(t_d)$ for 2000 and 3000 RPM runs were consistent (figures 3.4 and 3.5) and gave similar exponential coefficients and factors. The plot for the 1000 RPM case (figure 3.3) had a higher exponential coefficient and lower factor. All runs exhibited two distinct slopes - an early time slope associated with acceleration of the centrifuge to a stabilized RPM, and a late time slope associated with stabilized centrifugal displacement. The late time slope was used to calculate coefficients for Hagoort's calculations. The slope and intercept for the 1000 RPM case was more difficult to determine because of a smooth transition from the accelerating phase to the stabilized centrifugal displacement phase.

To verify Hagoort's model, plots of experimental versus calculated data (figures 5.3, 5.4, 5.5) were made using the equation:

$$N_p = 1 - \left[1 - \frac{1}{n}\right]\left[\frac{1}{k_{ro} n t_d}\right]^{\frac{1}{n-1}} \tag{5.2}$$

$N_p$ = cumulative production as a fraction of PV (pore volumes)

n = Hagoort's exponential coefficient

$k_{ro}$ = Hagoort's relative permeability

$t_d$ = dimensionless time

For all cases, the late time history match is adequate, but the early time match is poor because of centrifuge acceleration and the limitations of the functional relationship. This can also be verified by examining the $\ln(1 - N_p)$ versus $\ln(t_d)$ plots and noting that the straight line fit matches late time data but not early time data.

## 5.2 Coreflood and Centrifuge Model Sensitivities

Sensitivities to timestep length and cell size were tested on both the coreflood and centrifuge models to determine operating limitations. The coreflood model was stable for timesteps up to 5 seconds (figure 5.6) and showed an increasingly dispersed front as cell size increased. The centrifuge model became unstable (figure 5.7) for timesteps greater than 0.2 seconds. This instability was due to the explicit nature of the solution and was caused by large changes in saturation, relative permeability, or capillary pressure for individual cells. An internal check was installed to reduce timestep size if the saturation change was greater than 5% in any cell. An increasingly dispersed front was noted for both coreflooding and centrifuging as cell size increased (figures 5.8 and 5.9).

Model sensitivities that examined capillary pressure sensitivities showed that capillary pressure has a significant effect on both coreflooding and centrifuging, especially in early time before the advancing front has reached the outlet face. Capillary pressures caused dispersion of the advancing front for coreflooding (figure 5.10). Because centrifuging does not allow production of the injected phase, both frontal dispersion and delay of the advancing front was noted when capillary pressures were included (figure 5.11).

Sensitivities to variations in each of the Corey coefficients were run using history matched values for the 4000 RPM oil/water system. Each Corey coefficient was incremented by a fixed value while the two other coefficients remained constant. Results are summarized in figures 5.12, 5.13, and 5.14. The production seemed most sensitive to the wetting phase coefficient C1 and least sensitive to the nonwetting phase factor C3.

## 5.3 History Match vs Graphically-Derived Relative Permeability Curves

Centrifuge History Match Summary

| Sample | System | Centrifuge Speed | C1 | C2 | C3 | $S_{wir}$ |
|---|---|---|---|---|---|---|
| BA-2A | water/oil | 4000 | 4.26 | 12.43 | .10 | 0.10 |
| BA-2A | water/oil | 4000 | did not converge | | | 0.32 |
| BA-2C | water/oil | 3000 | 5.0 | 10.0 | 1.0 | 0.10 |
| BA-2C | water/oil | 3000 | did not converge | | | 0.32 |
| BA-1A | gas/oil | 1000 | 4.99 | 8.52 | 0.95 | 0.10 |
| BA-1A | gas/oil | 2000 | 5.21 | 11.11 | 0.95 | 0.10 |
| BA-1A | gas/oil | 3000 | 5.02 | 8.64 | 0.95 | 0.10 |

The coreflood and centrifuge models were history matched using initial guesses from the Jones-Roszelle and Hagoort graphical techniques. Tolerances were varied between $10^{-2}$ and $10^{-3}$ PV and irregular history match points were smoothed to allow the model to converge within a reasonable time limit. Most centrifuge model runs converged within 20-25 iterations or came within a reasonable error limit. Plots of experimental data versus simulation history match data for both the oil/water (figures 5.15, 5.16) and gas/oil (figures 5.17, 5.18, 5.19) systems show good matches in both early time and late time.

A plot of experimental pressure drop across the core versus model pressure drop (figure 19a) shows that the model pressure drop is lower than experimental pressure drop. The coreflood model history matched only the fluid production data. The relative permeabilities obtained by the history matching algorithm were used to calculate the pressure drop in the core. This indicates that further adjustment of the relative permeabilities is needed to properly account for the change in pressure across the core. This can be implemented by including an additional term in the least squares history match algorithm that accounts for pressure drop across the core.

An additional set of water/oil centrifuge runs were completed that used the irreducible wetting phase saturation from the Jones-Roszelle coreflood displacement analysis ($S_{wir}$ = 0.32). The 3000 and 4000 RPM runs did not have did not have sufficient wetting phase volume for an accurate history match.

Coreflood History Match Summary

| Sample | System | C1 | C2 | C3 | $S_{wir}$ |
|---|---|---|---|---|---|
| BA-2 | Oil/Water | 3.66 | 1.87 | 1.0 | 0.10 |
| BA-2 | Oil/Water | 1.71 | 0.40 | 0.30 | 0.32 |

Oil/water coreflood runs were more difficult to history match, particularly early time data. Although a good match was obtained for late time data (figure 5.20), early time matching was difficult even after curve smoothing the input data. More early time coreflood data and measurement of injection rate, breakthrough time, and production data for both the wetting and nonwetting phases would verify whether the model's assumption of constant injection rate was correct.

The oil/water coreflood run using the Jones-Roszelle $S_{wir} = 0.32$ gave a worse history match (figure 5.20A) than using the endpoint saturation form capillary pressure tests ($S_{wir} = 0.10$). This implies that the $S_{wir}$ obtained from the Jones-Roszelle technique is too high.

A comparison of oil/water history matched Corey curves for 3000 and 4000 RPM (figure 5.21) showed that the lower RPM system had a higher C3 factor on the nonwetting phase term. The wetting phase curves for both RPM's matched adequately. The gas/oil system curves at 1000 and 3000 RPM (figure 5.22) matched closely for both phases. This close match can be explained by the small variation of the wetting phase coefficient C1, since the simulation model response is much more sensitive to this parameter than it is to C2 and C3. The 2000 RPM nonwetting curves match is average, probably due to the curve smoothing of irregular data in early time.

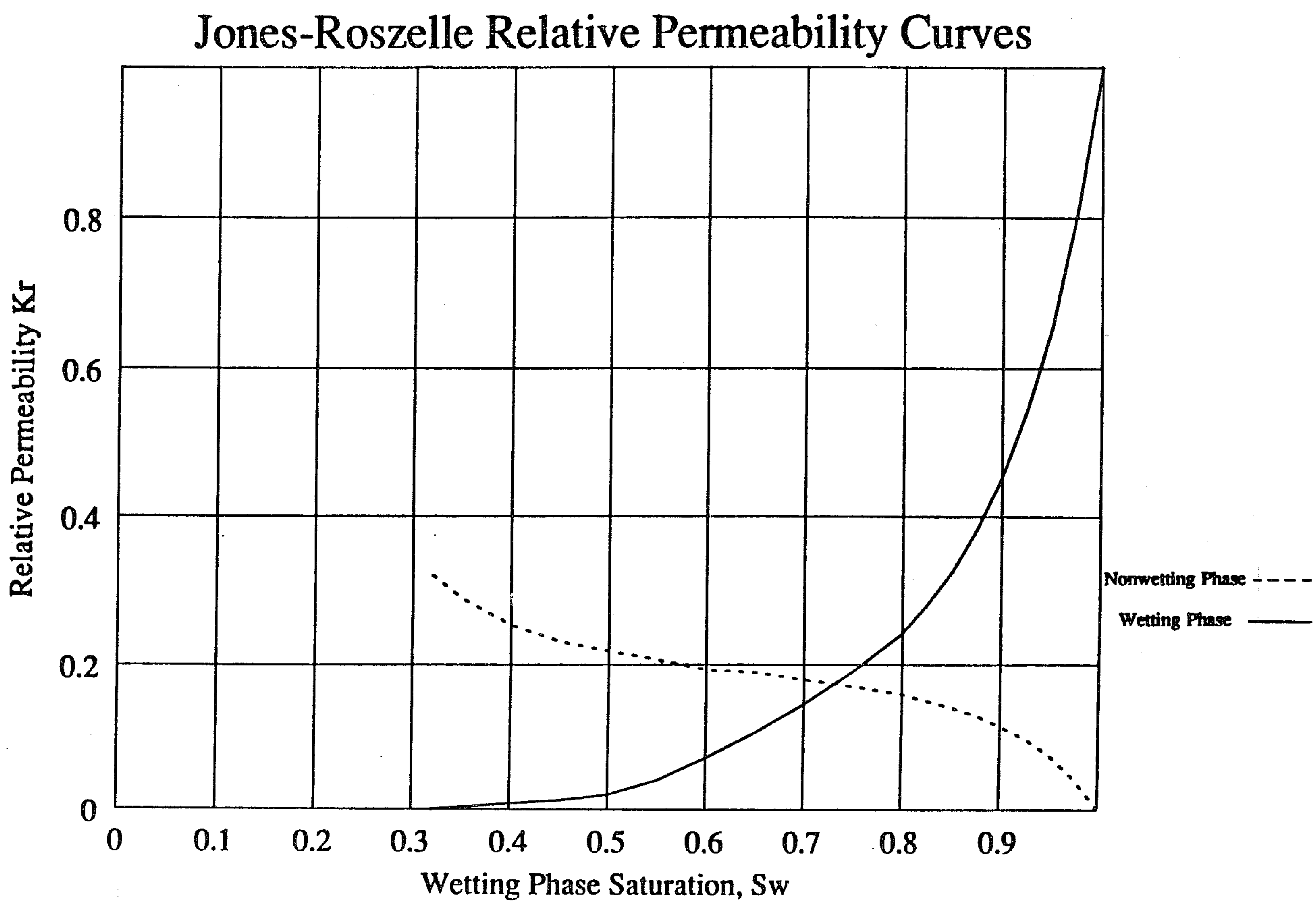
A comparison of Jones-Roszelle relative permeability curves versus history match relative permeability curves (figure 5.23) for the oil/water coreflood showed a good correlation with both sets of curves skewed toward higher water saturations. The major difference between the two sets of curves was the lower relative permeability of both phases for the Jones-Roszelle analysis. This is probably due to measurement error of tangent point saturations and effective viscosities.

The gas/oil history matched centrifuge curves for 2000 and 3000 RPM compared favorably with the wetting phase curves derived from Hagoort's method (figures 5.25, 5.26). This favorable match is due to the fact that both approaches use the same relative permeability (Corey's formula) and have similar exponential coefficients (n = C1 = 5.0). The 1000 RPM curves were a poor match, probably because of the difficulties associated with determining the proper slope and intercept using Hagoort's method.

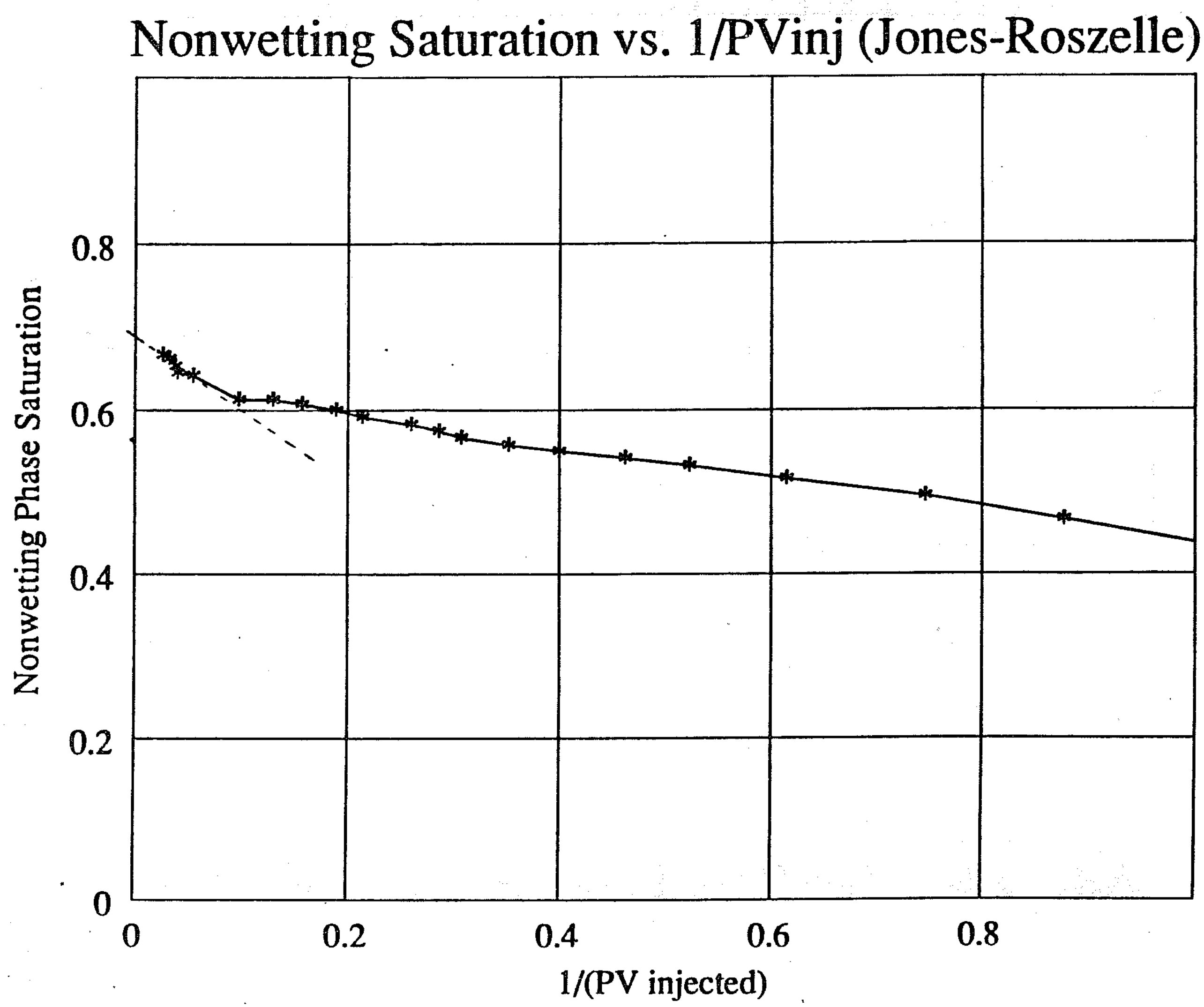
5.4 Comparison of Coreflood versus Centrifuge Relative Permeability Curves

The final comparison between centrifuge relative permeability curves and coreflood relative permeability curves (figure 5.27) showed a very good correlation for the wetting phase curves, but completely different shapes for the nonwetting phase curves. The Jones-Roszelle graphical technique implied a much higher irreducible water saturation for coreflooding than centrifuging ($S_{wir,coreflood} = 0.32$ versus $S_{wir,centrifuge} = 0.10$). This difference in endpoints has a large effect on the shape of the nonwetting phase curve. It may be necessary to run the centrifuge at an injection rate comparable to the coreflood displacement rate. This could be accomplished by running the centrifuge at a lower RPM (500-1000) and using the centrifuge history match model to determine an average production rate throughout the run. This average production rate could be used as the injection rate for the coreflood experiment.

The most significant difference between coreflooding versus centrifuge relative permeability curves appears to be the irreducible water saturation ($S_{wir}$). Does centrifugal acceleration apply abnormally high force to the pore spaces and reduce $S_{wir}$ to unrealistically low values? Or does unsteady state coreflooding leave a residual $S_{wir}$ that is too high because the experiment is not run long enough? It appears that the Jones-Roszelle coreflood $S_{wir}$ is too high, but this answer is inadequate because we do not have good understanding of the physics of pore-to-pore movement of oil, gas, and water. A model that includes compressible fluid effects would provide a more accurate simulation of both coreflooding and centrifuging for the gas/oil system. Also, CATSCANs of experimental coreflooding and centrifuging at various times throughout the run may give useful insights into saturations profiles before and after break-through.



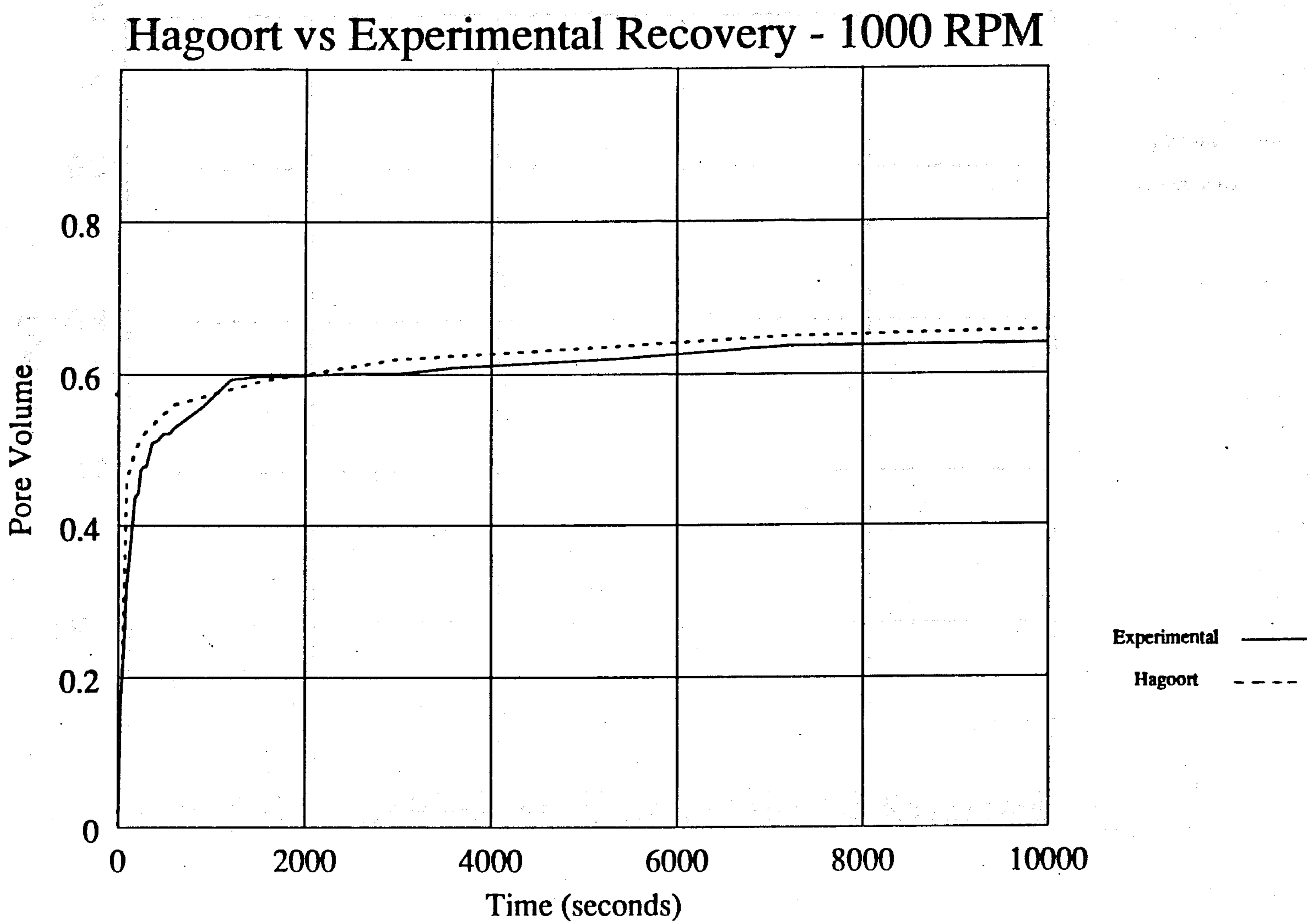

5.1 Water/oil Jones-Roszelle relative permeability



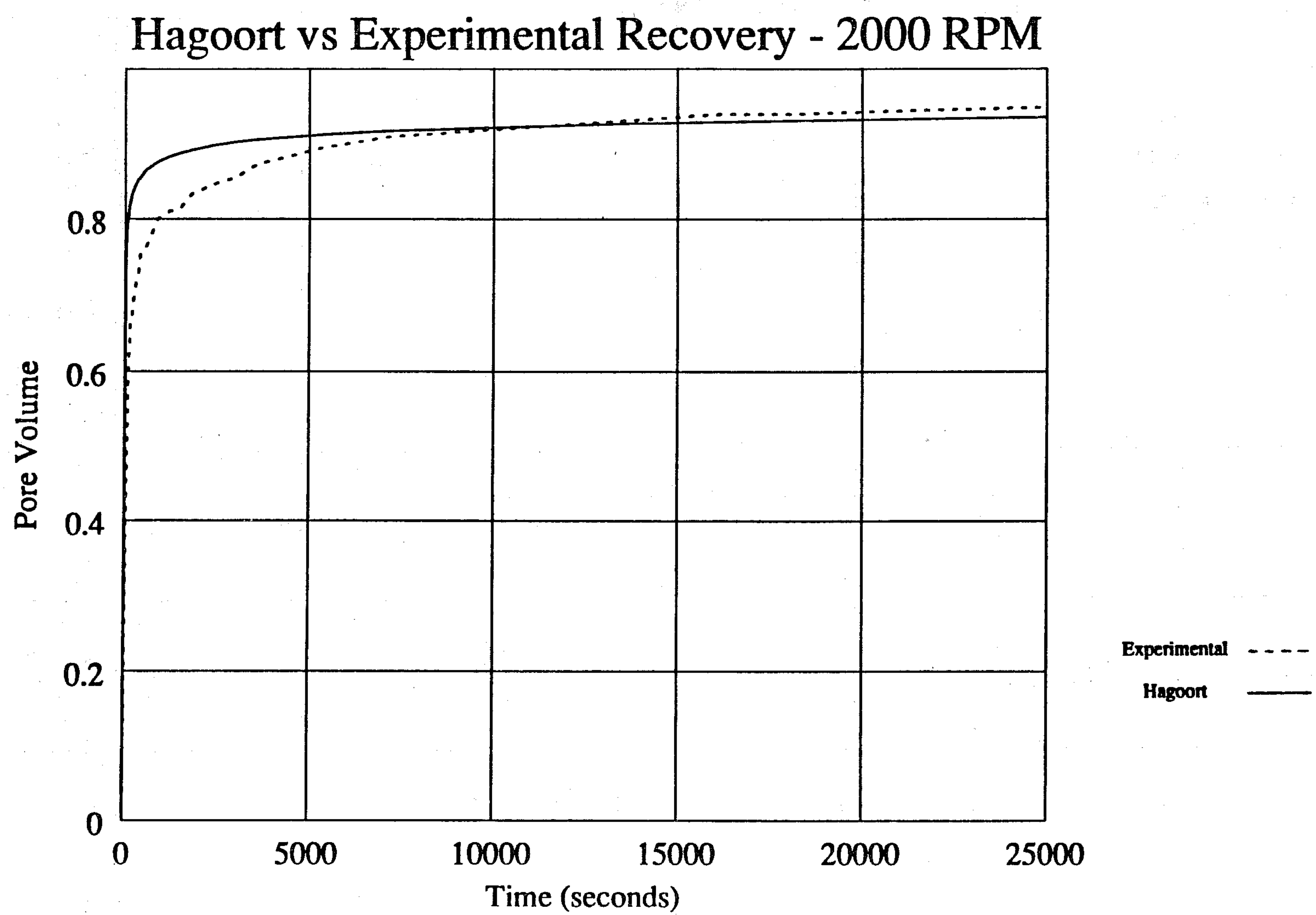

$S_n = 0.68$

$S_{wir} = 1.0 - 0.68 = 0.32$

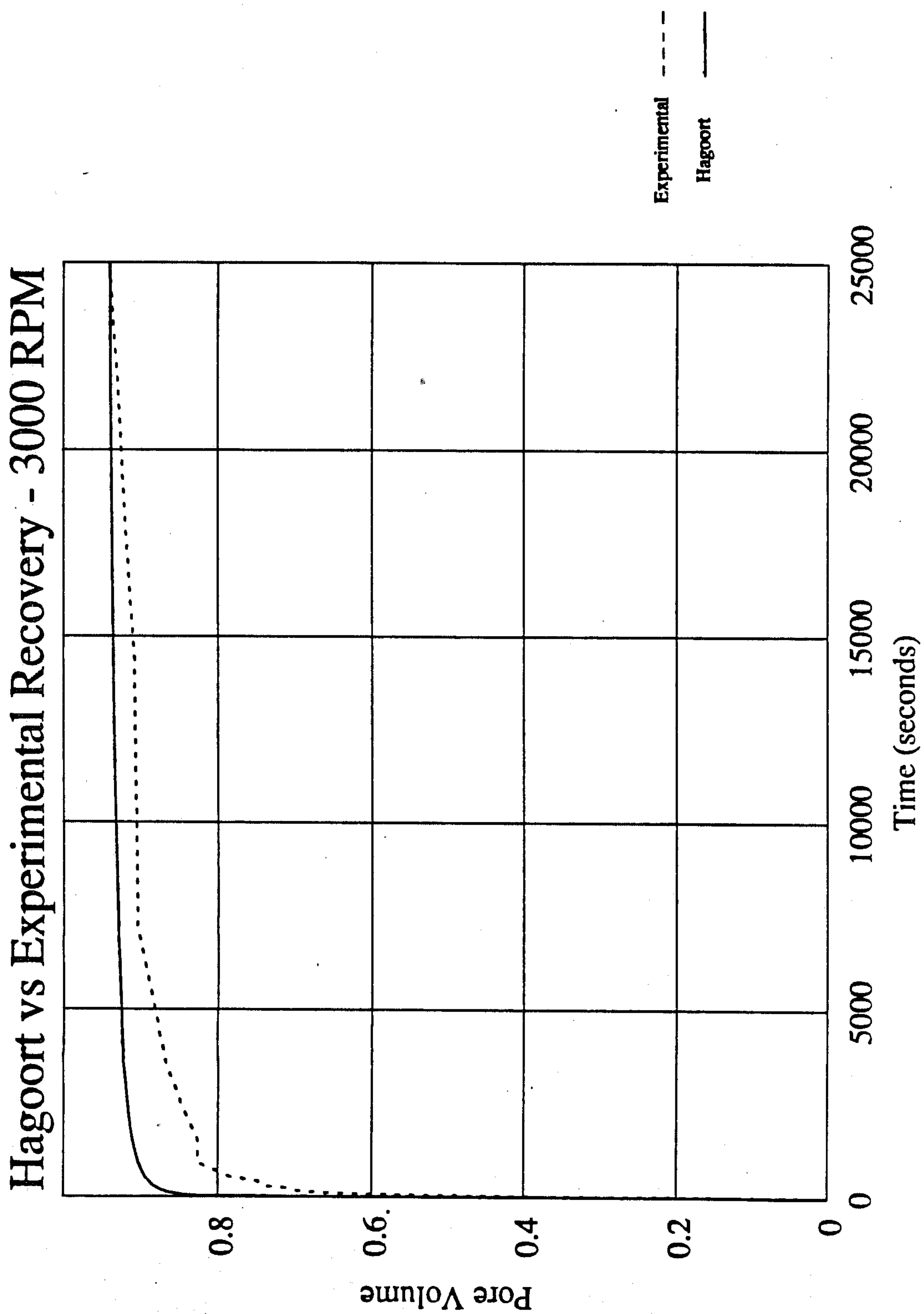
5.2 Water saturation vs. $(1/PV_{inj})$



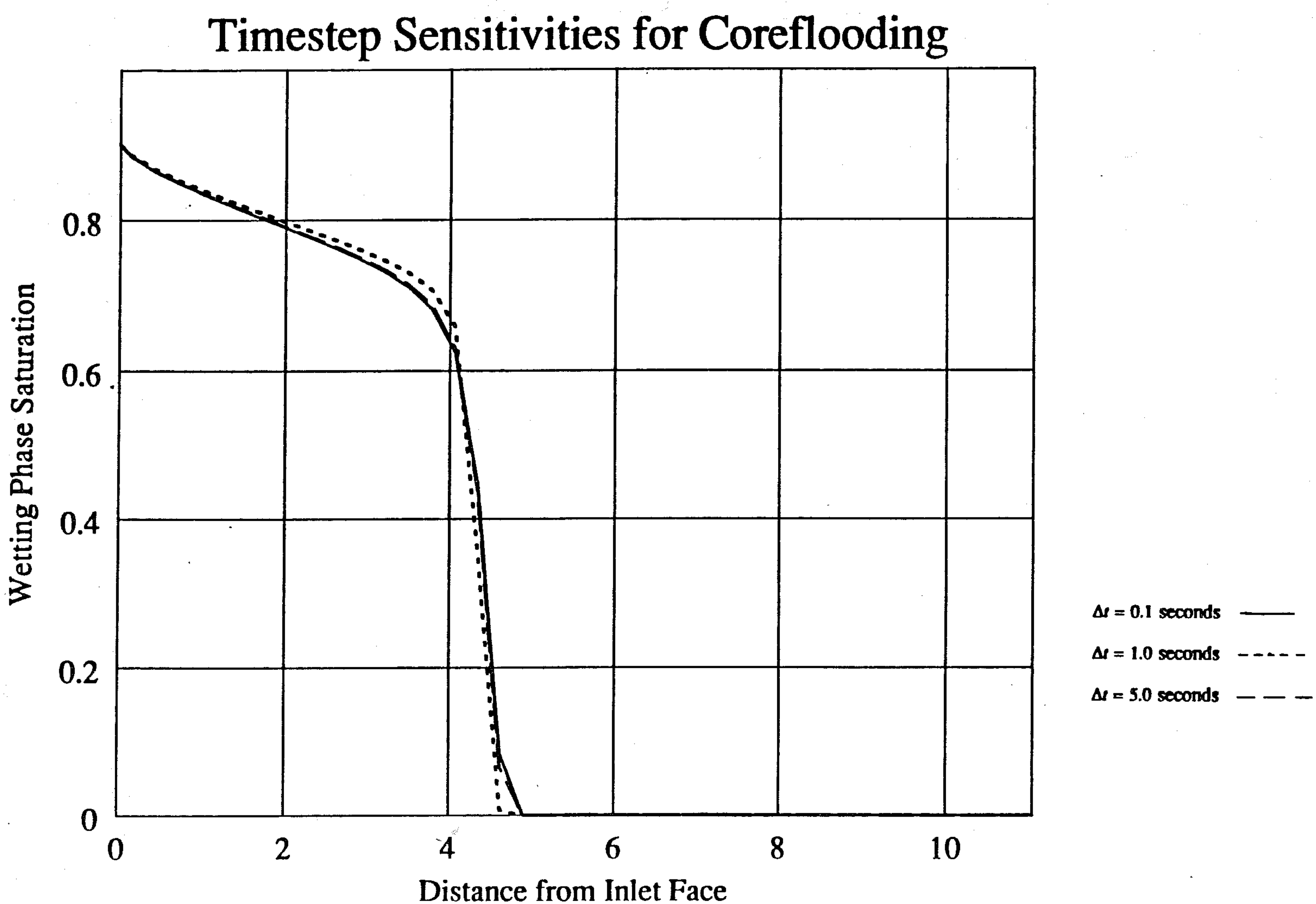

5.3 Hagoort vs. experimental recovery - 1000 RPM



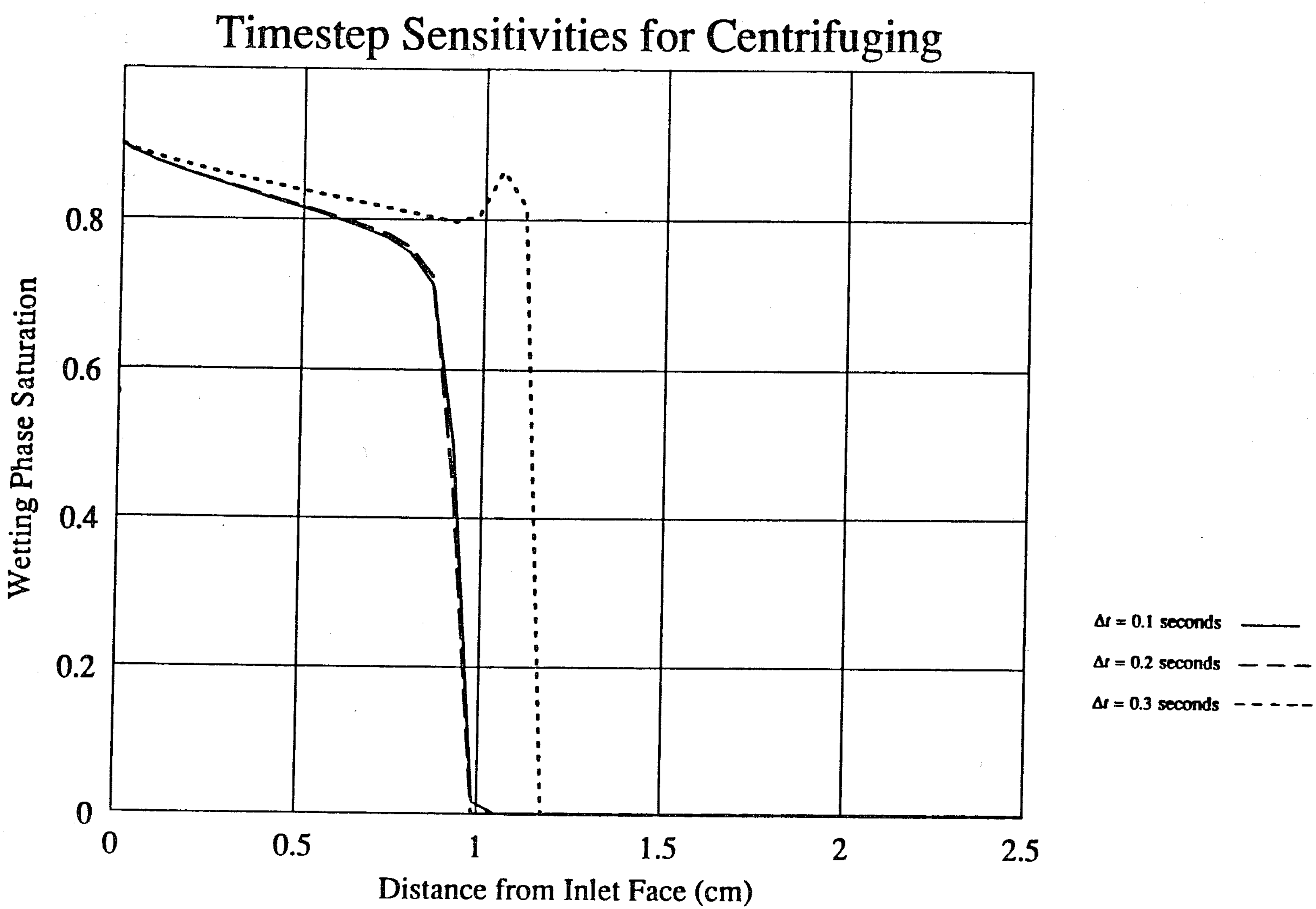

5.4 Hagoort vs. experimental recovery - 2000 RPM



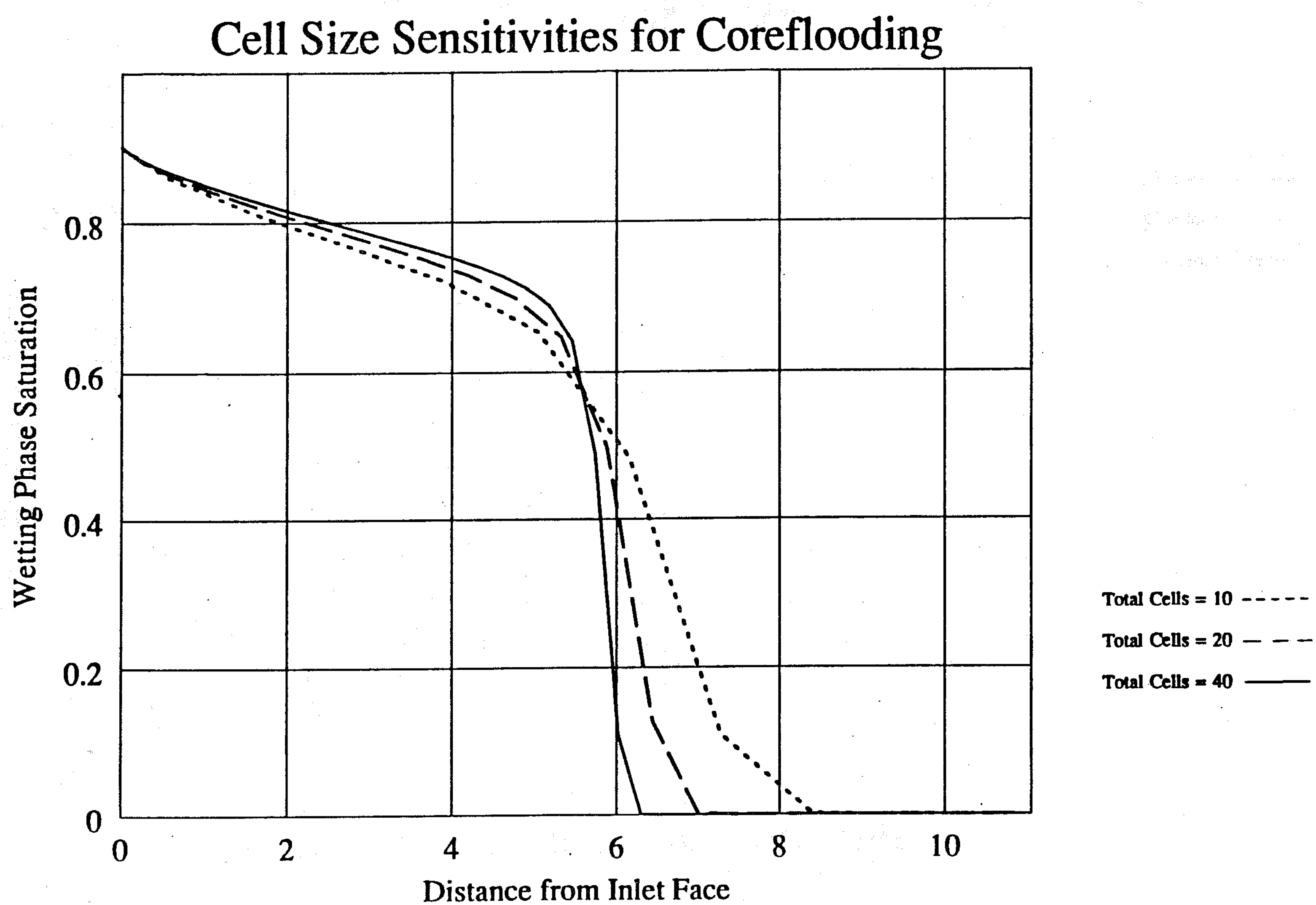

5.5 Hagoort vs. experimental recovery - 3000 RPM



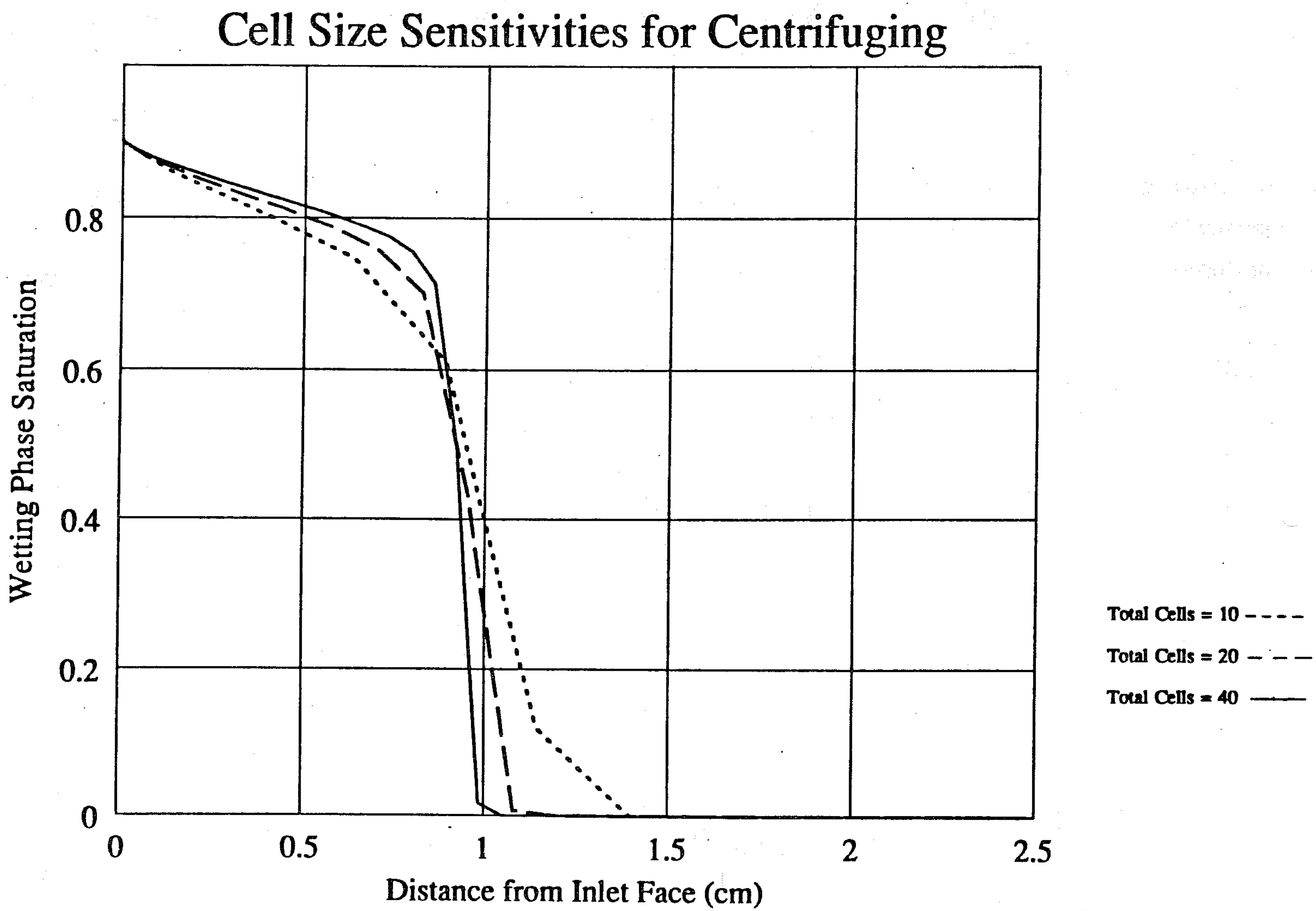

5.6 Timestep sensitivities for coreflooding



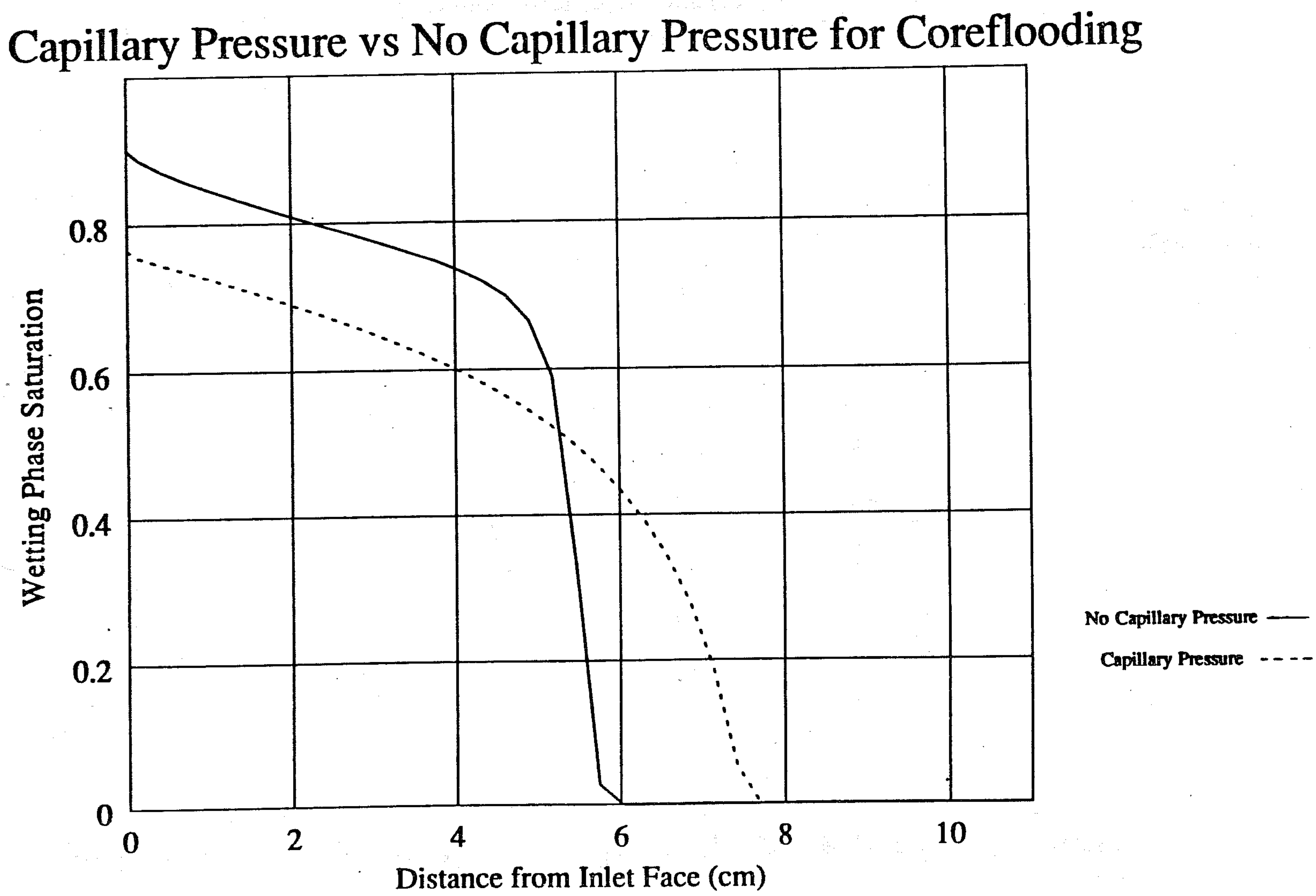

5.7 Timestep sensitivities for centrifuging



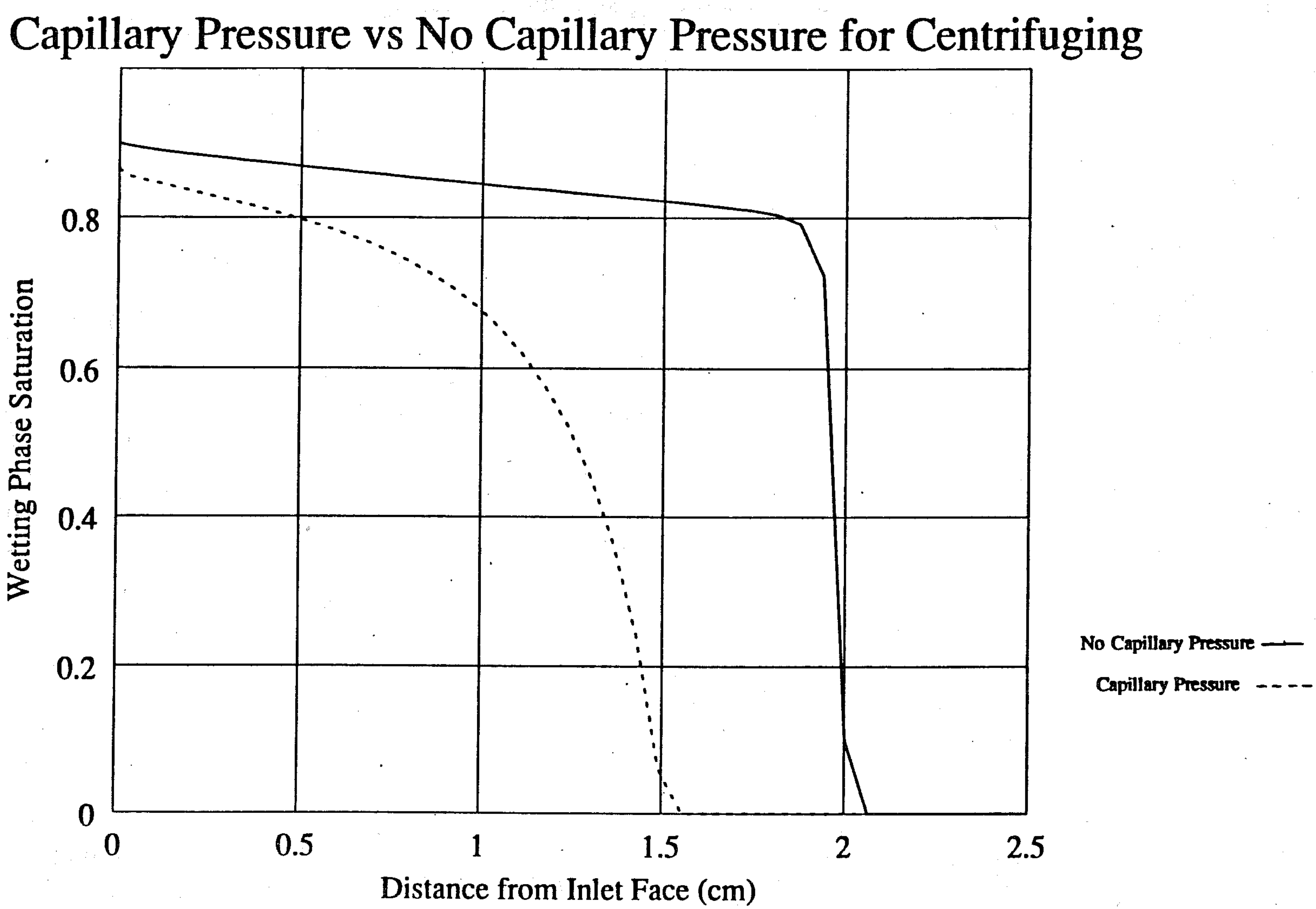

5.8 Cell size sensitivities for coreflooding



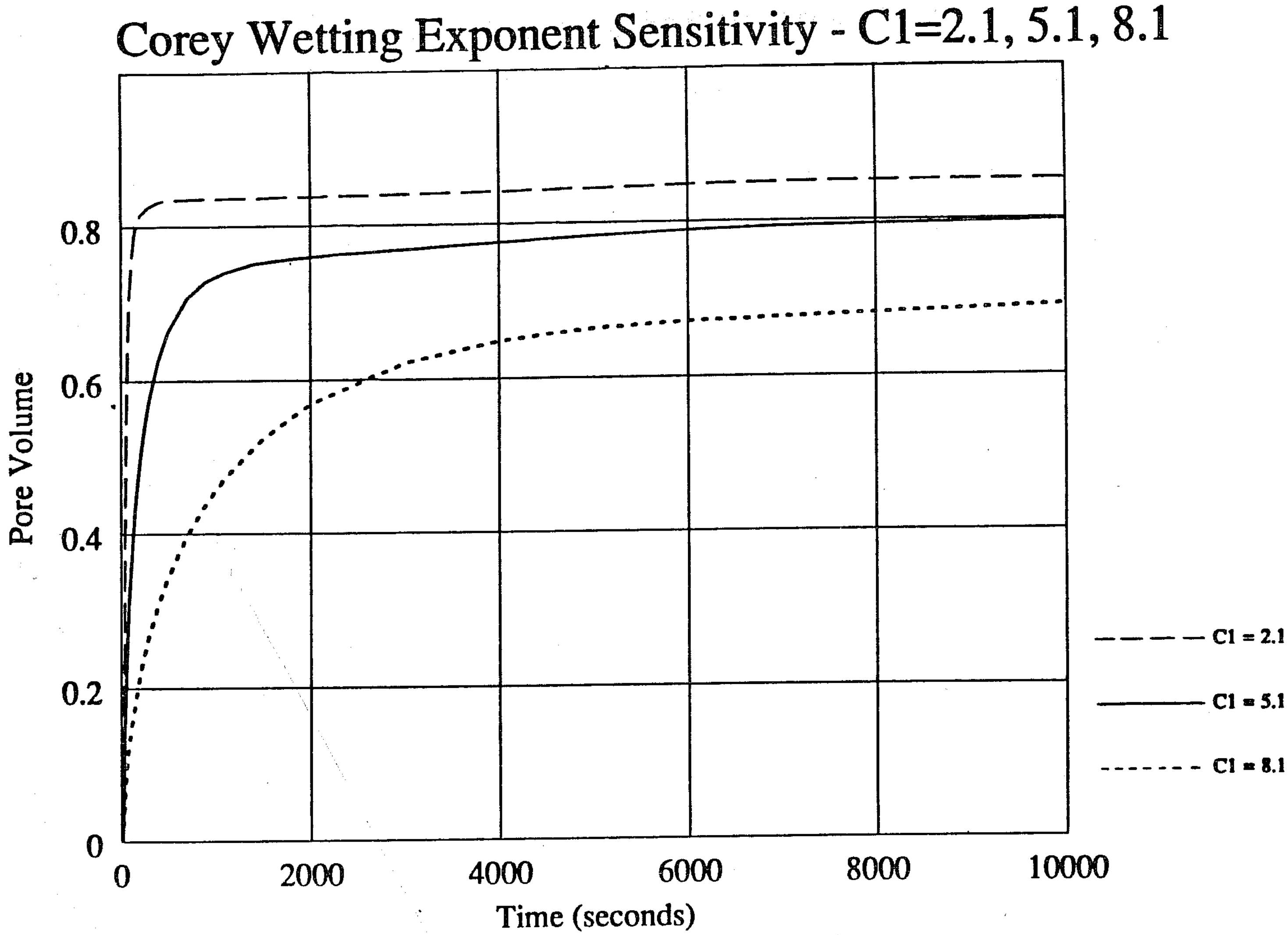

5.9 Cell size sensitivities for centrifuging



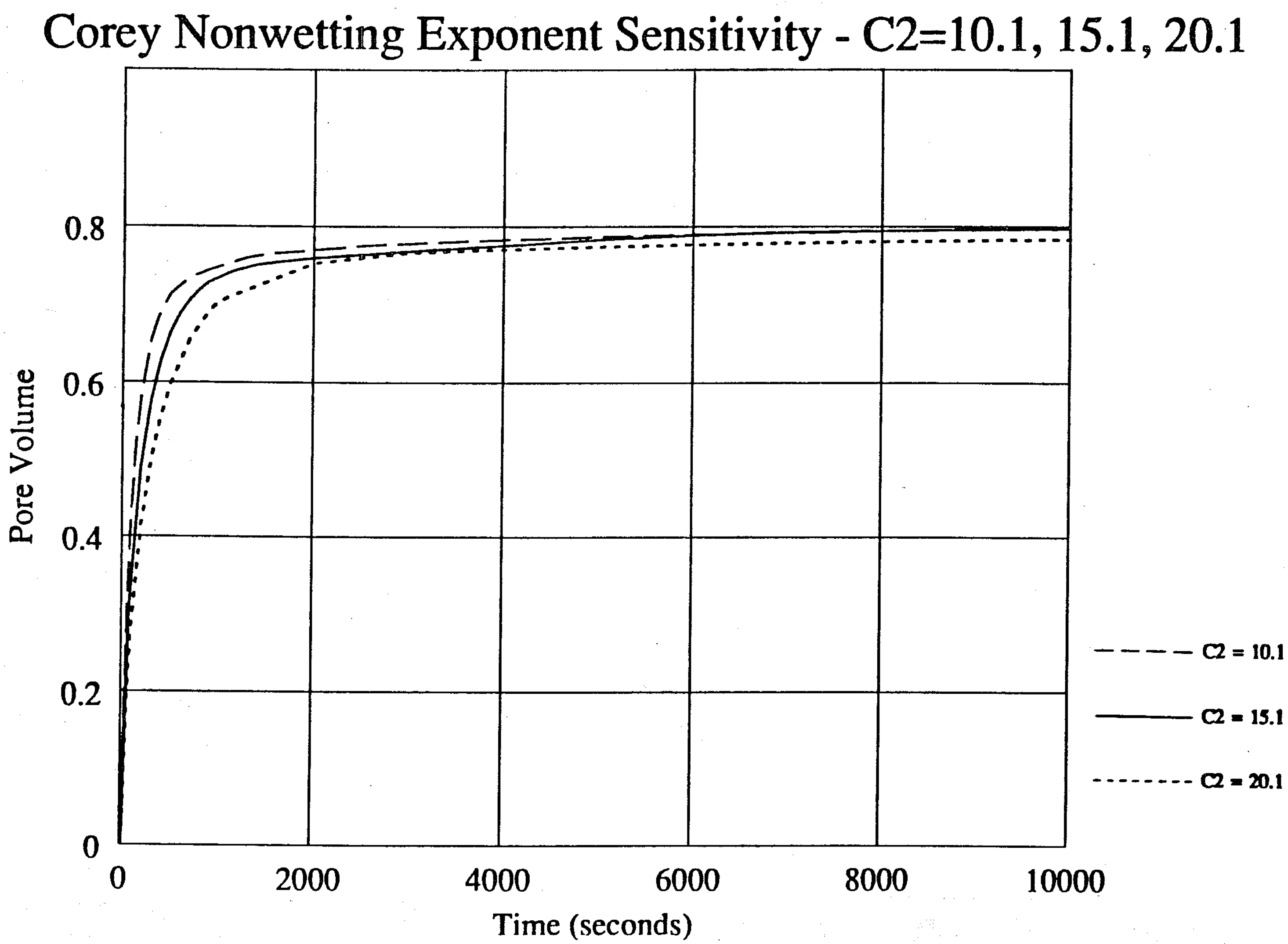

5.10 Capillary pressure sensitivities for coreflooding



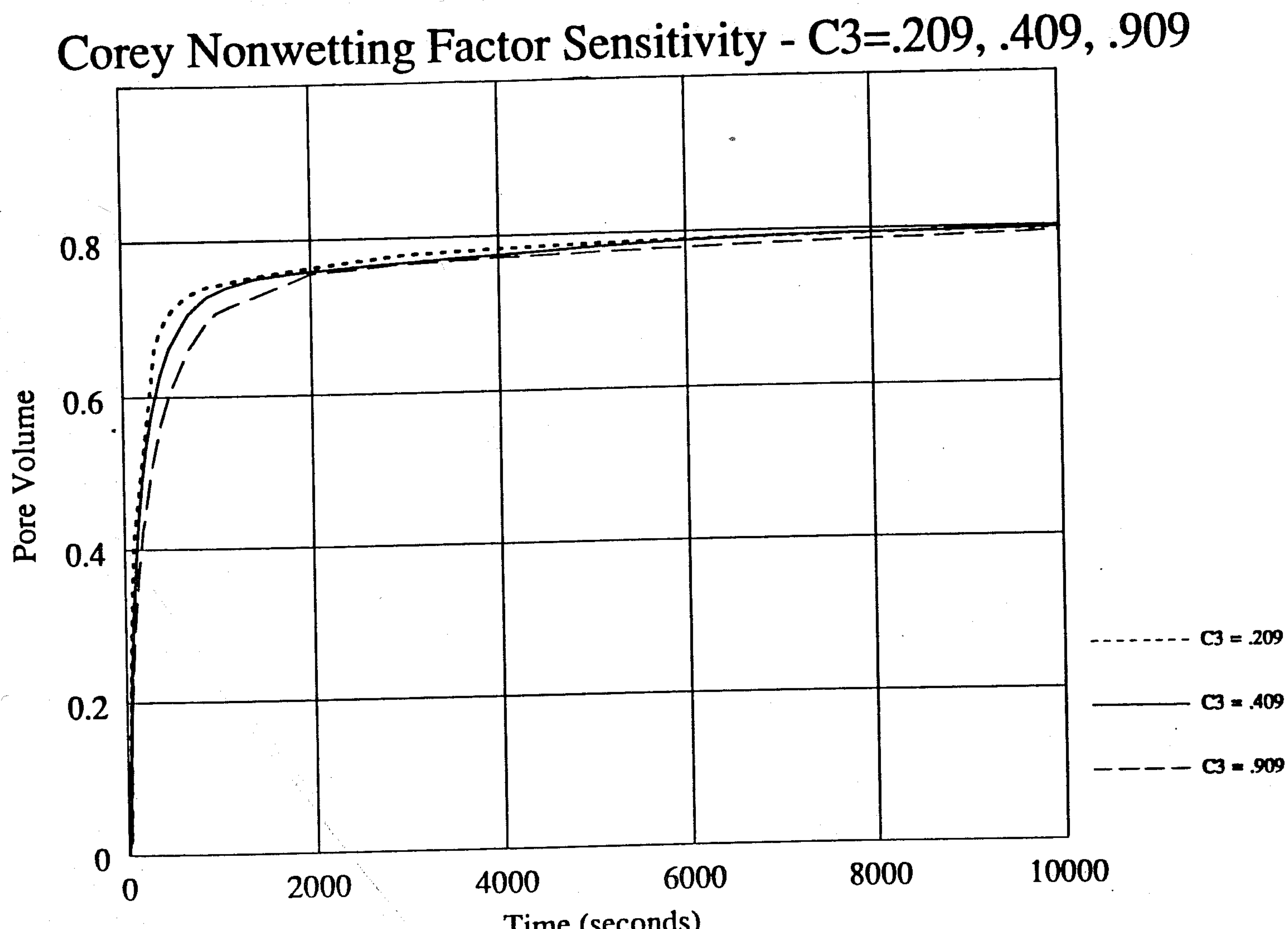

5.11 Capillary pressure sensitivities for centrifuging



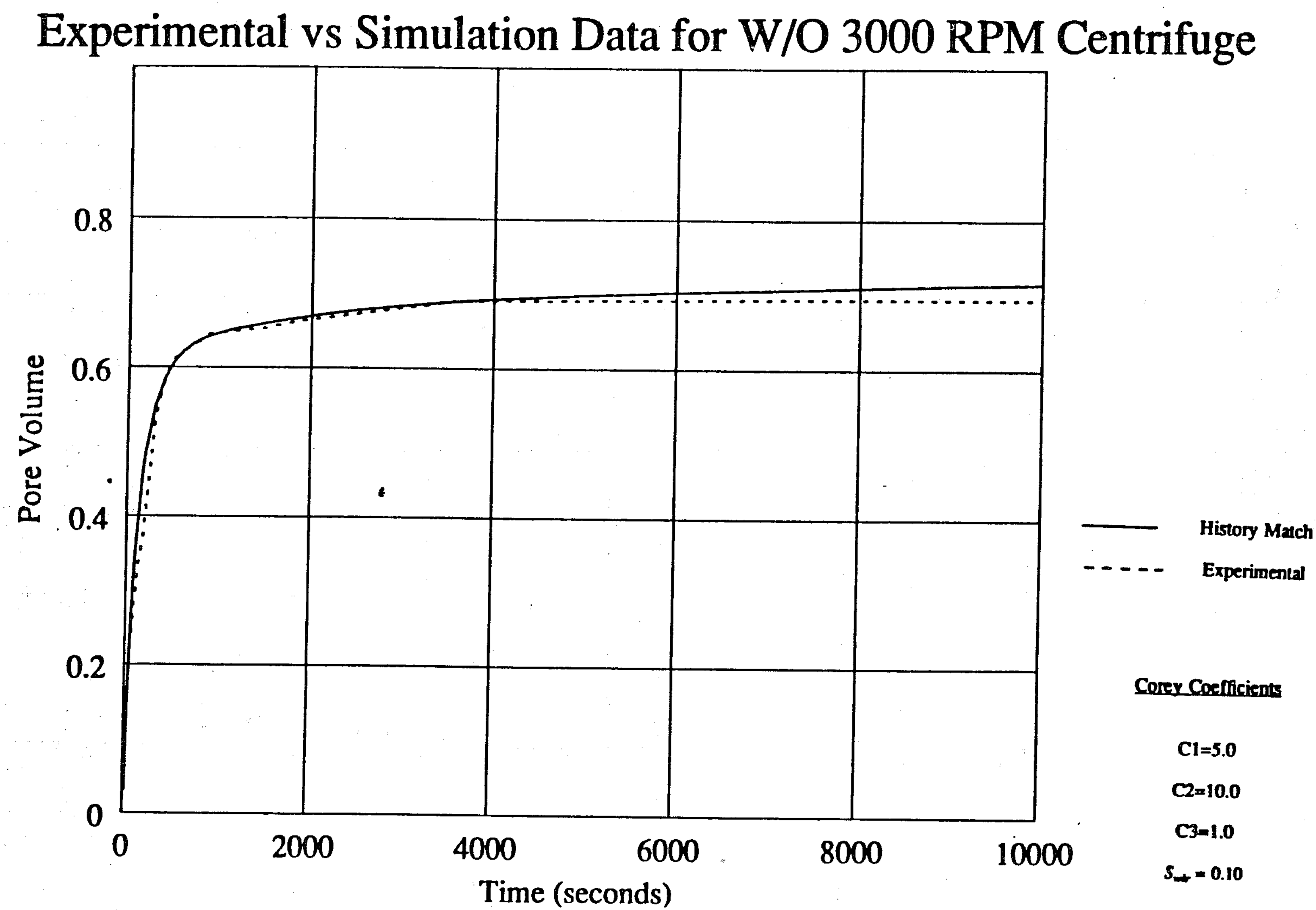

5.12 Corey sensitivity for wetting phase exponential term



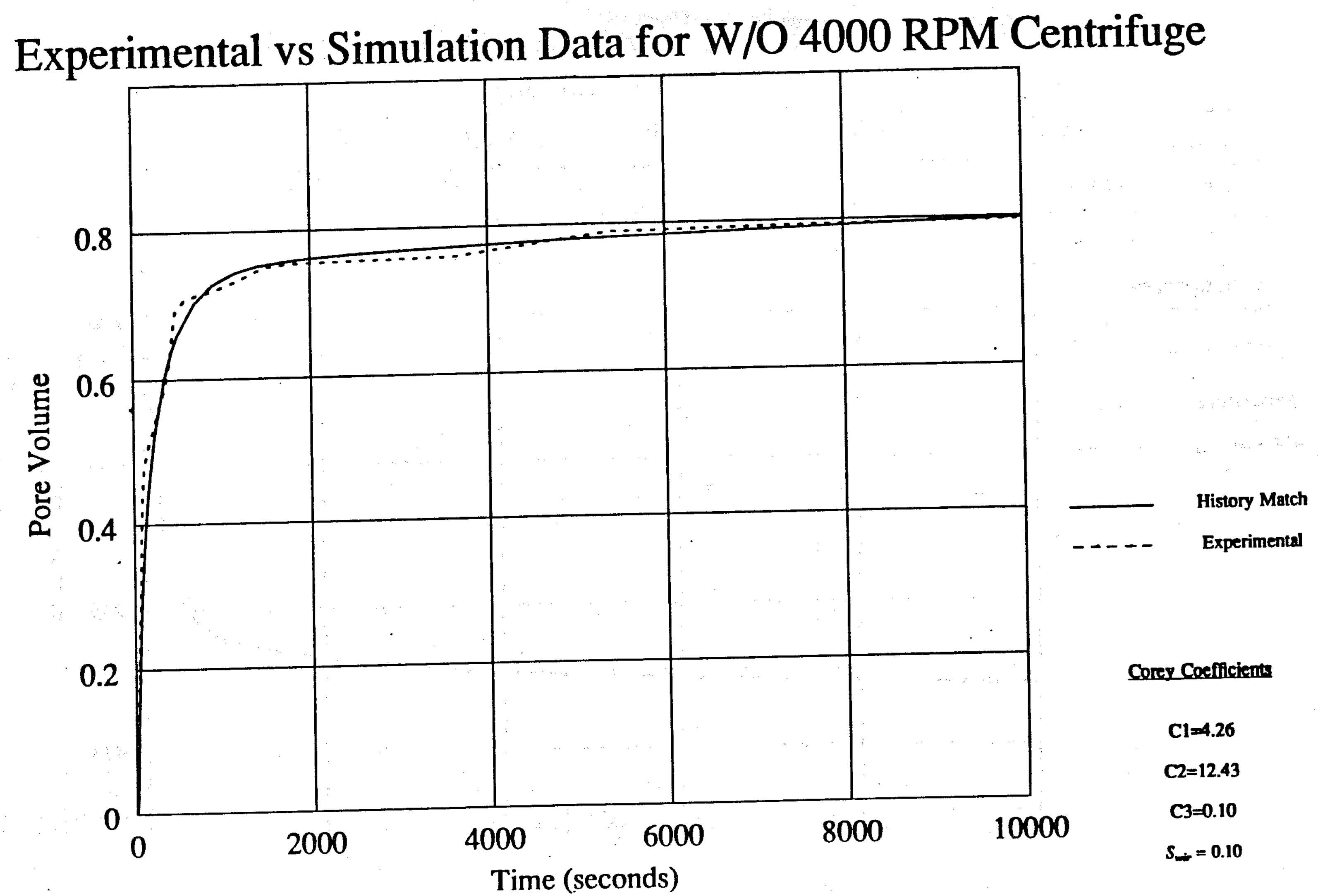

5.13 Corey sensitivity for nonwetting phase exponential term



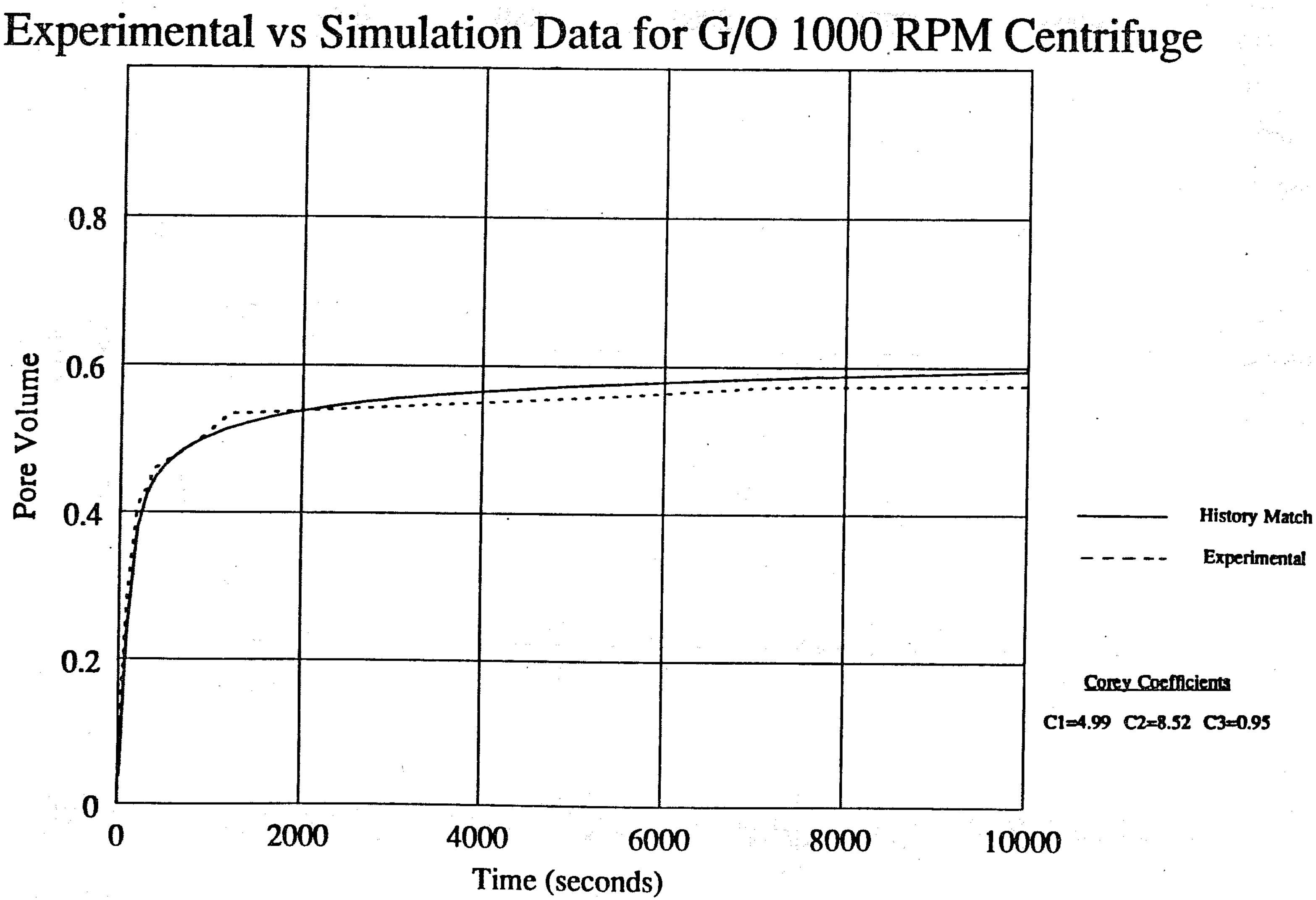

5.14 Corey sensitivity for nonwetting phase factor



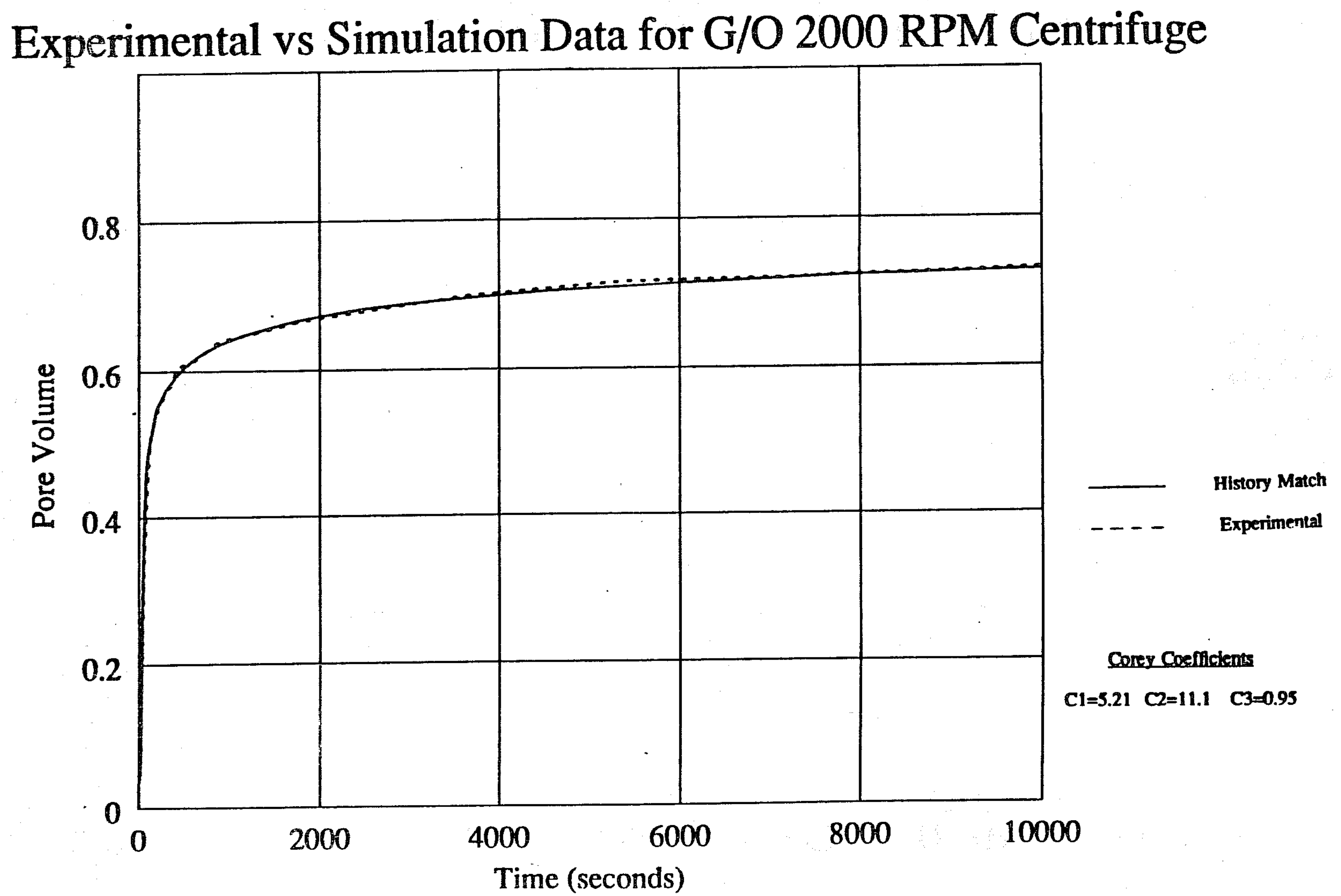

5.15 Experimental vs. simulation data for 3000 RPM oil/water



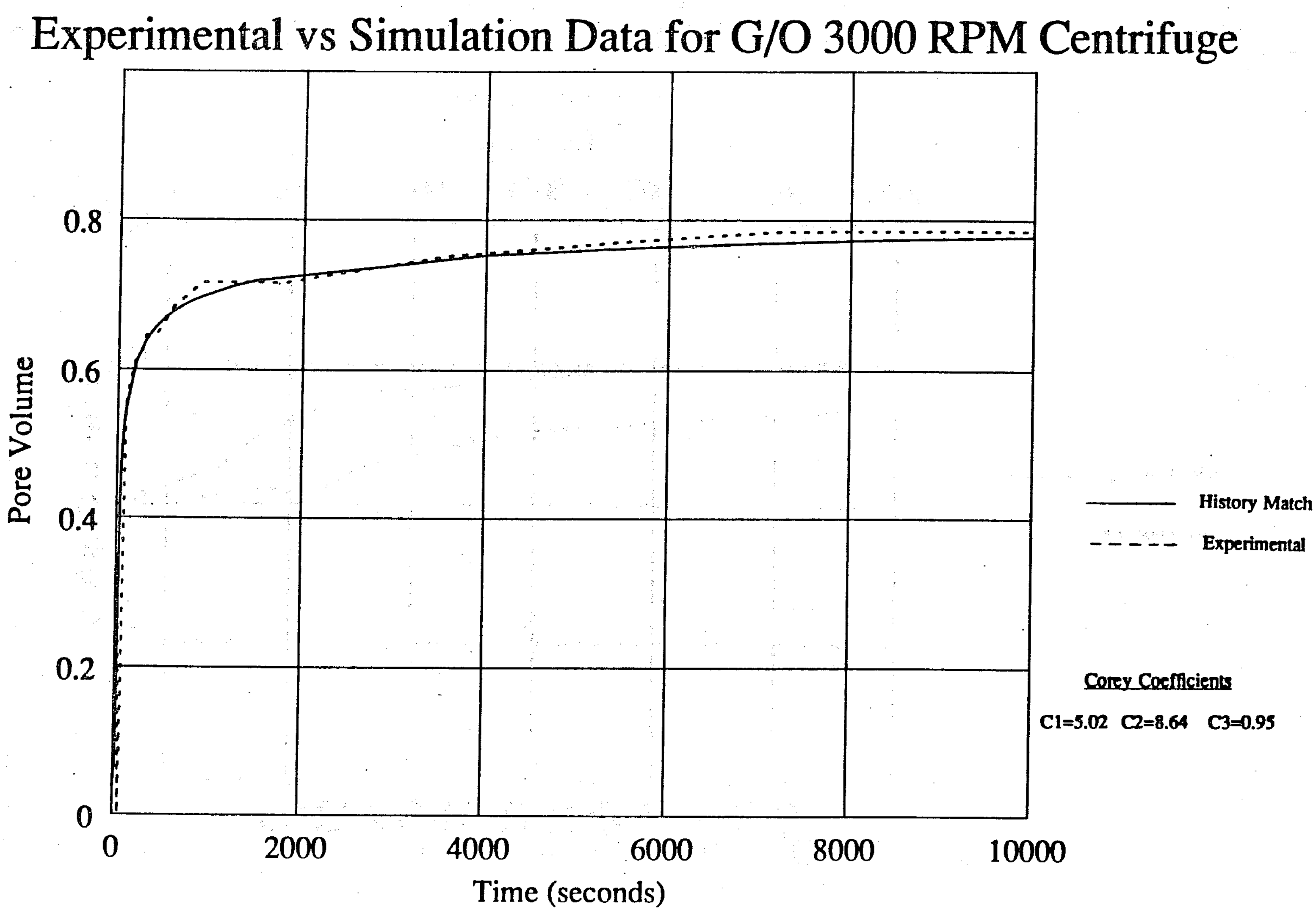

5.16 Experimental vs. simulation data for 4000 RPM oil/water



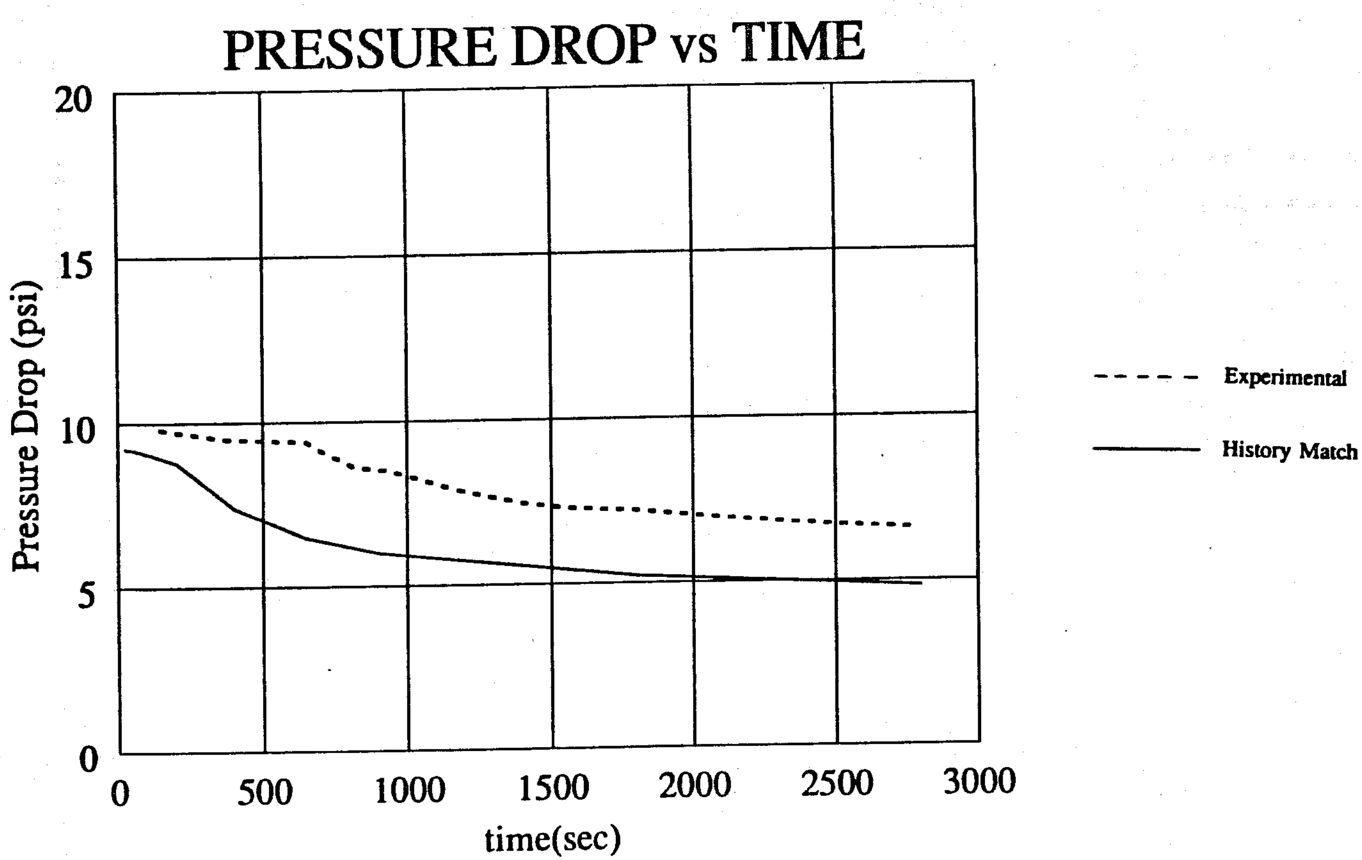

5.17 Experimental vs. simulation data for 1000 RPM gas/oil



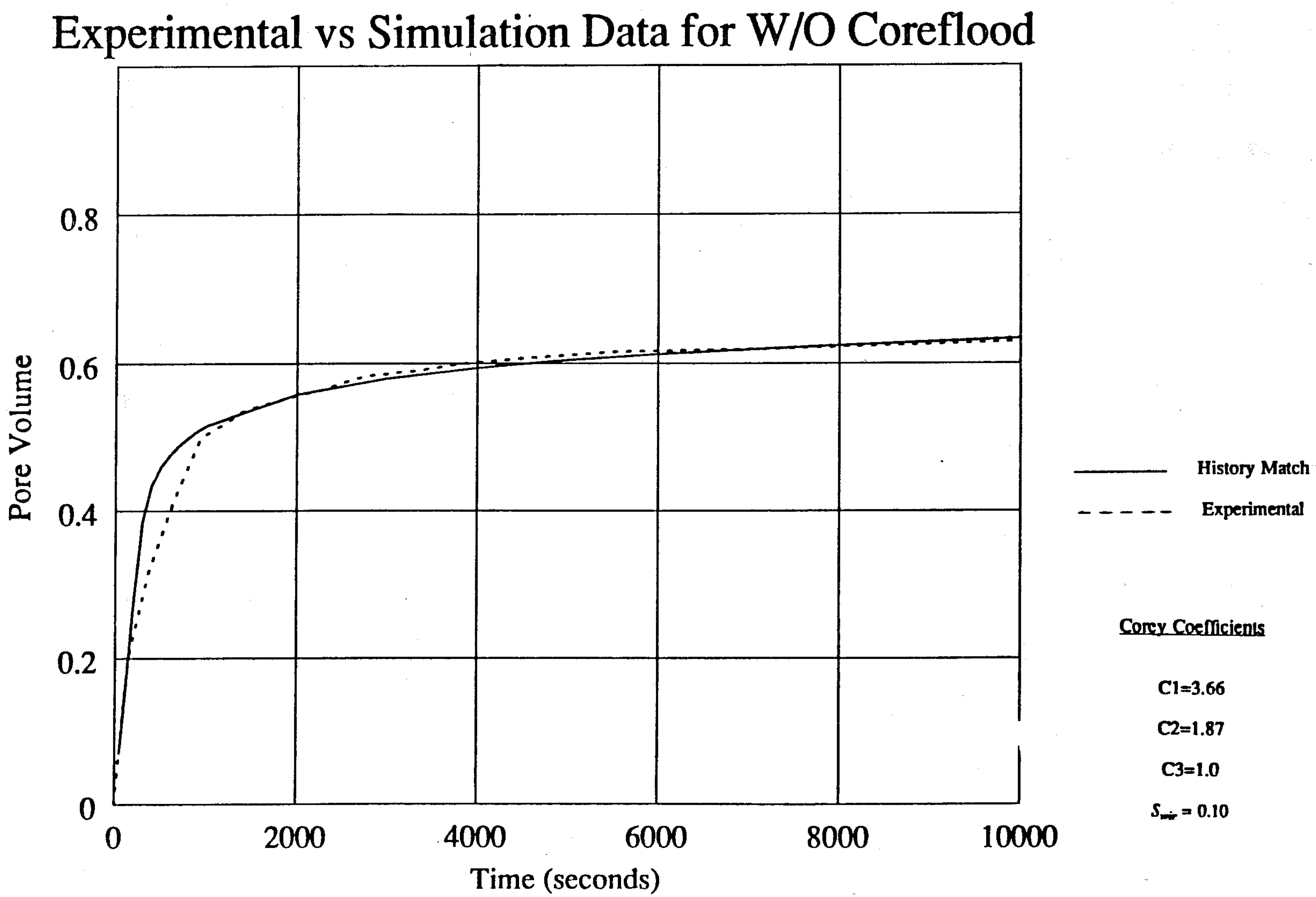

5.18 Experimental vs. simulation data for 2000 RPM gas/oil



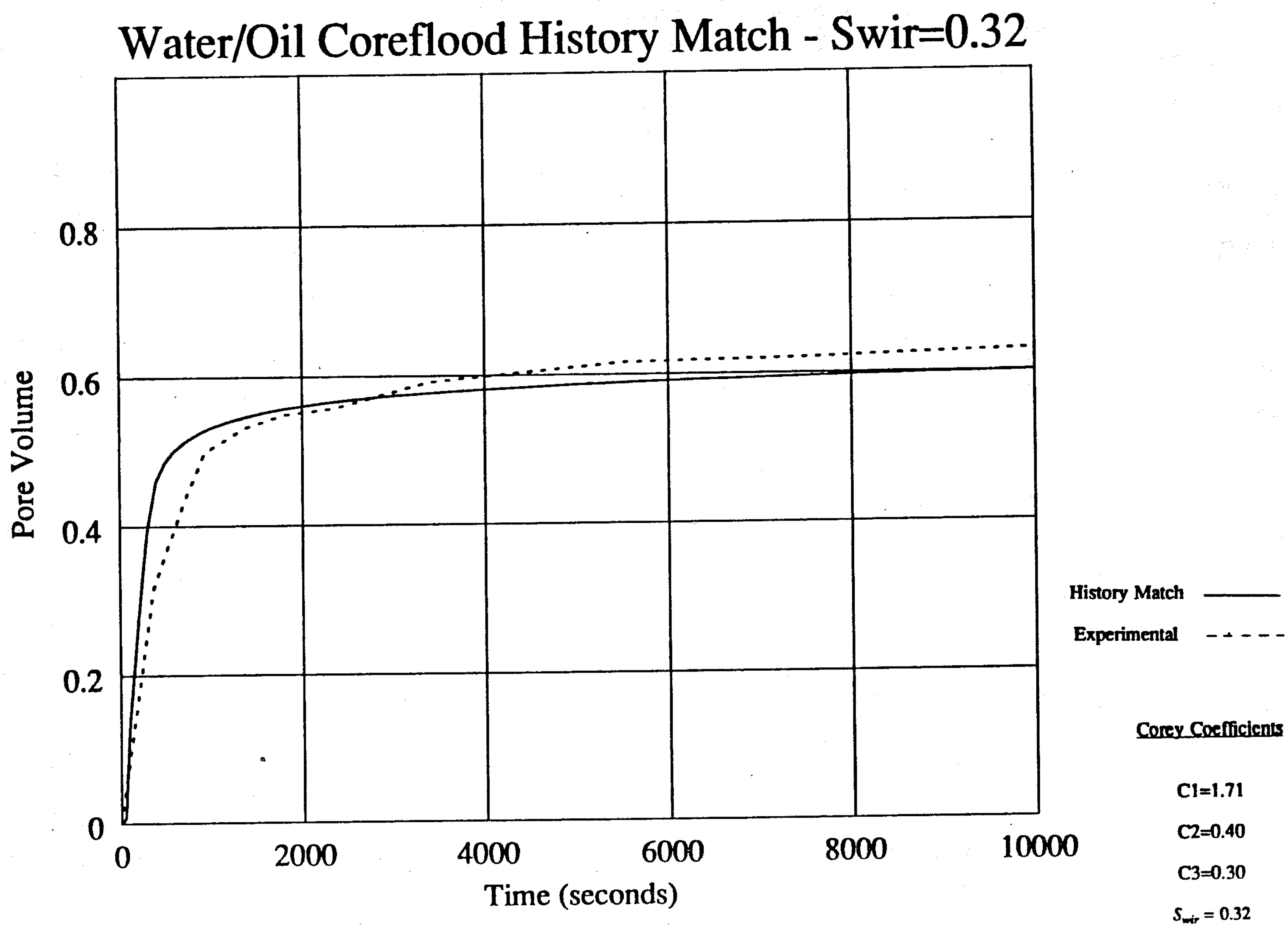

5.19 Experimental vs. simulation data for 3000 RPM gas/oil



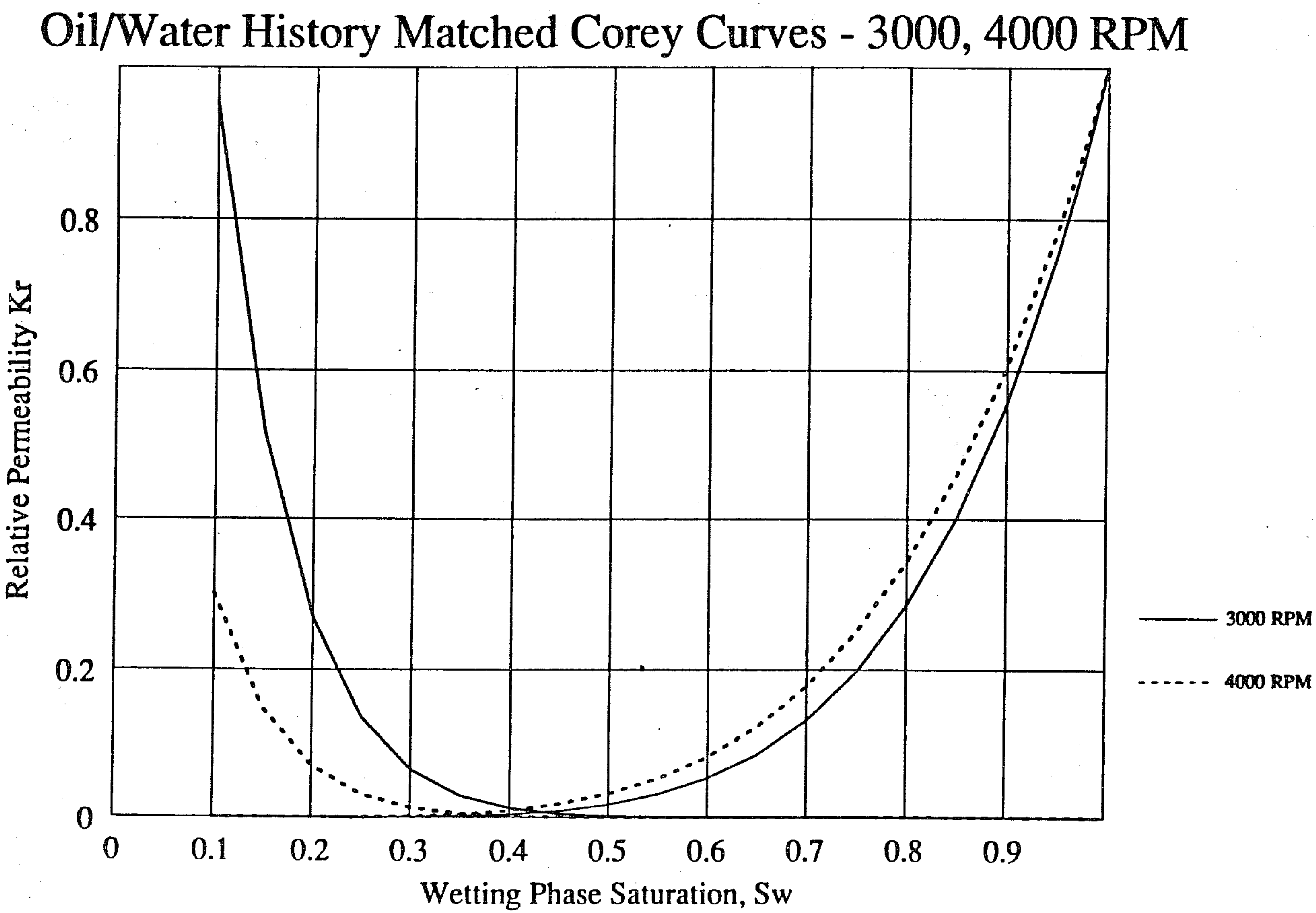

5.19a Experimental vs. model pressure drop



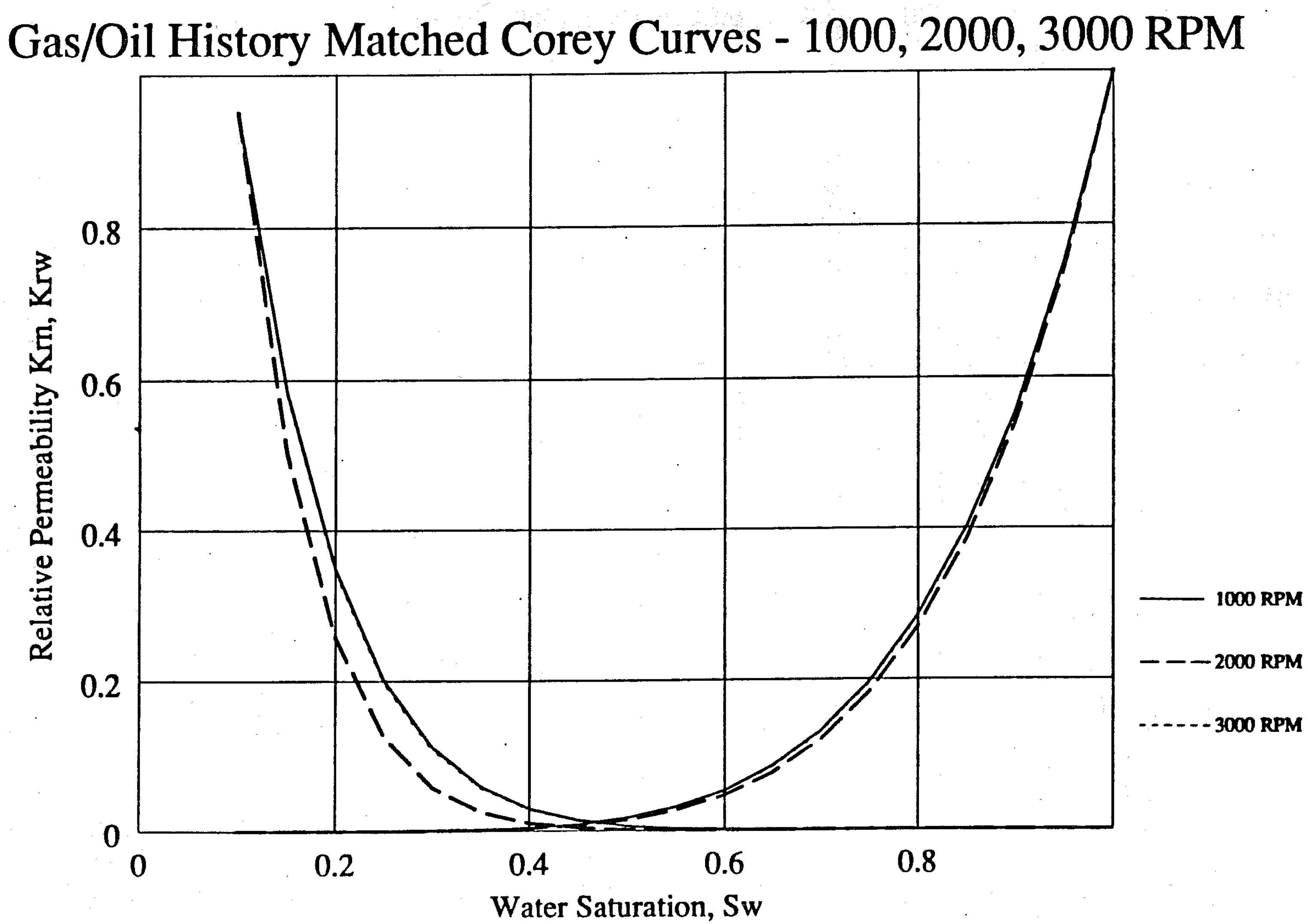

5.20 Experimental vs. simulation data for oil/water coreflood



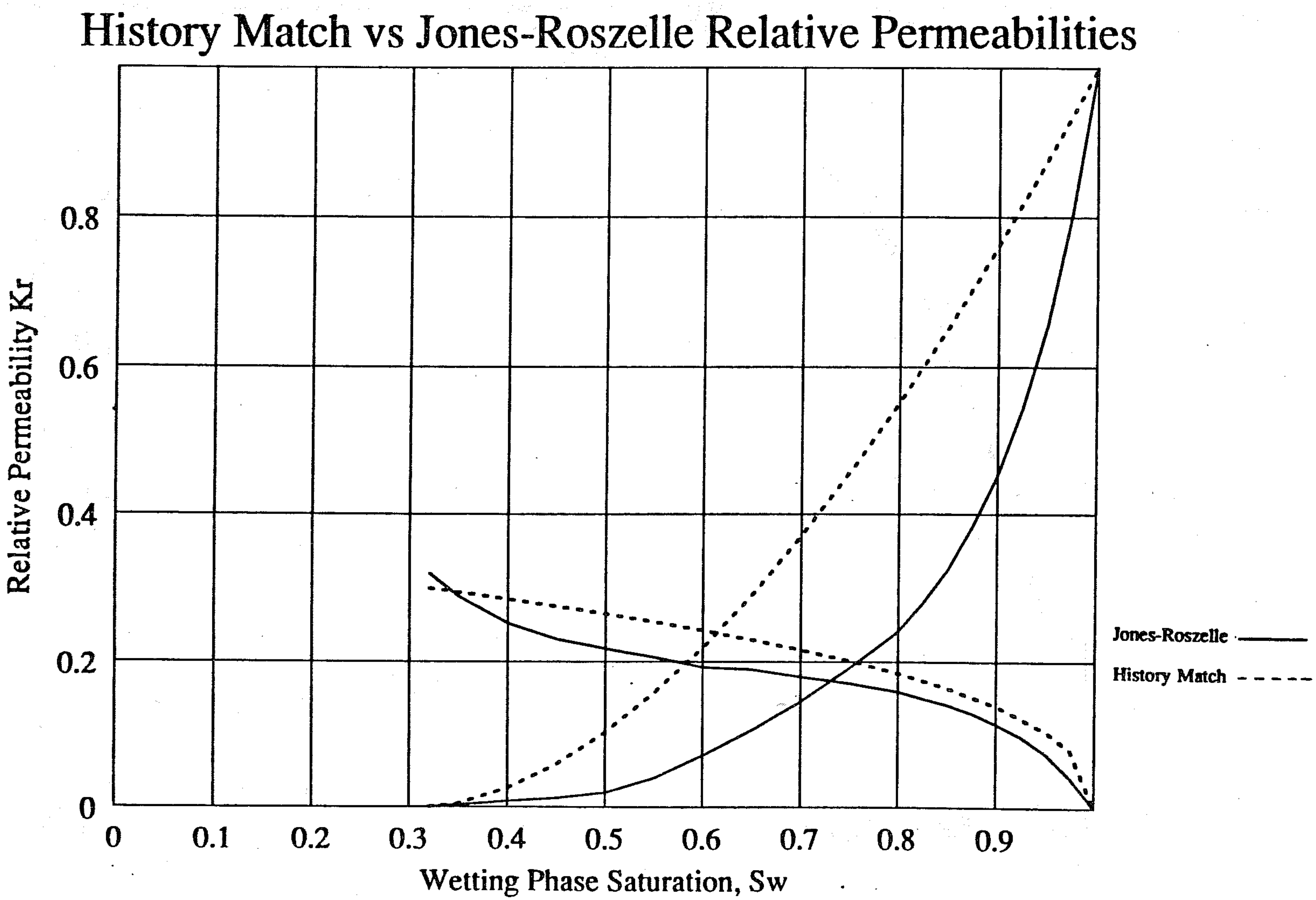

5.20a Water/oil coreflood history match, $S_{wir} = 0.32$



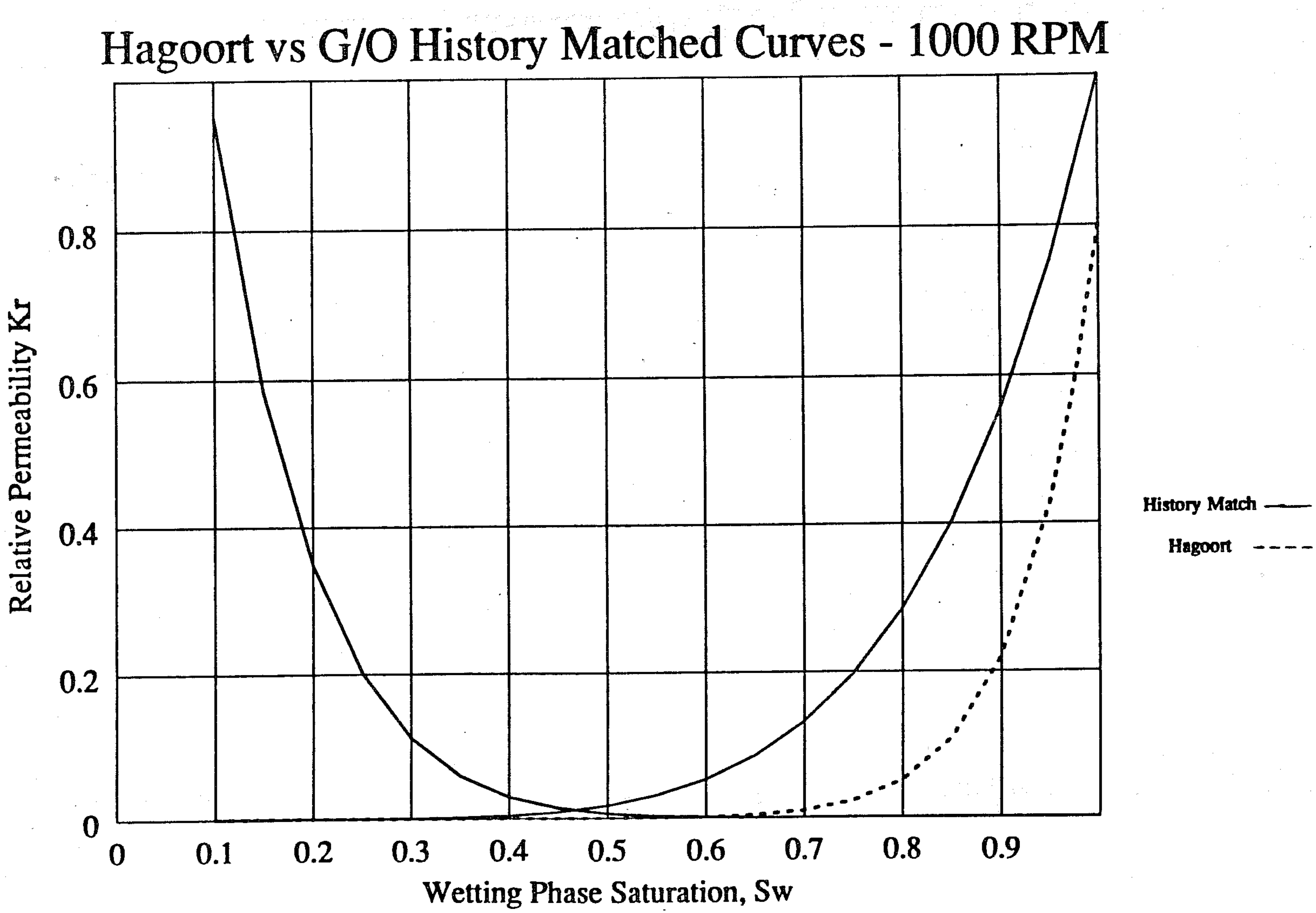

5.21 Comparison of 3000 RPM vs. 4000 RPM history matched curves for the oil/water system



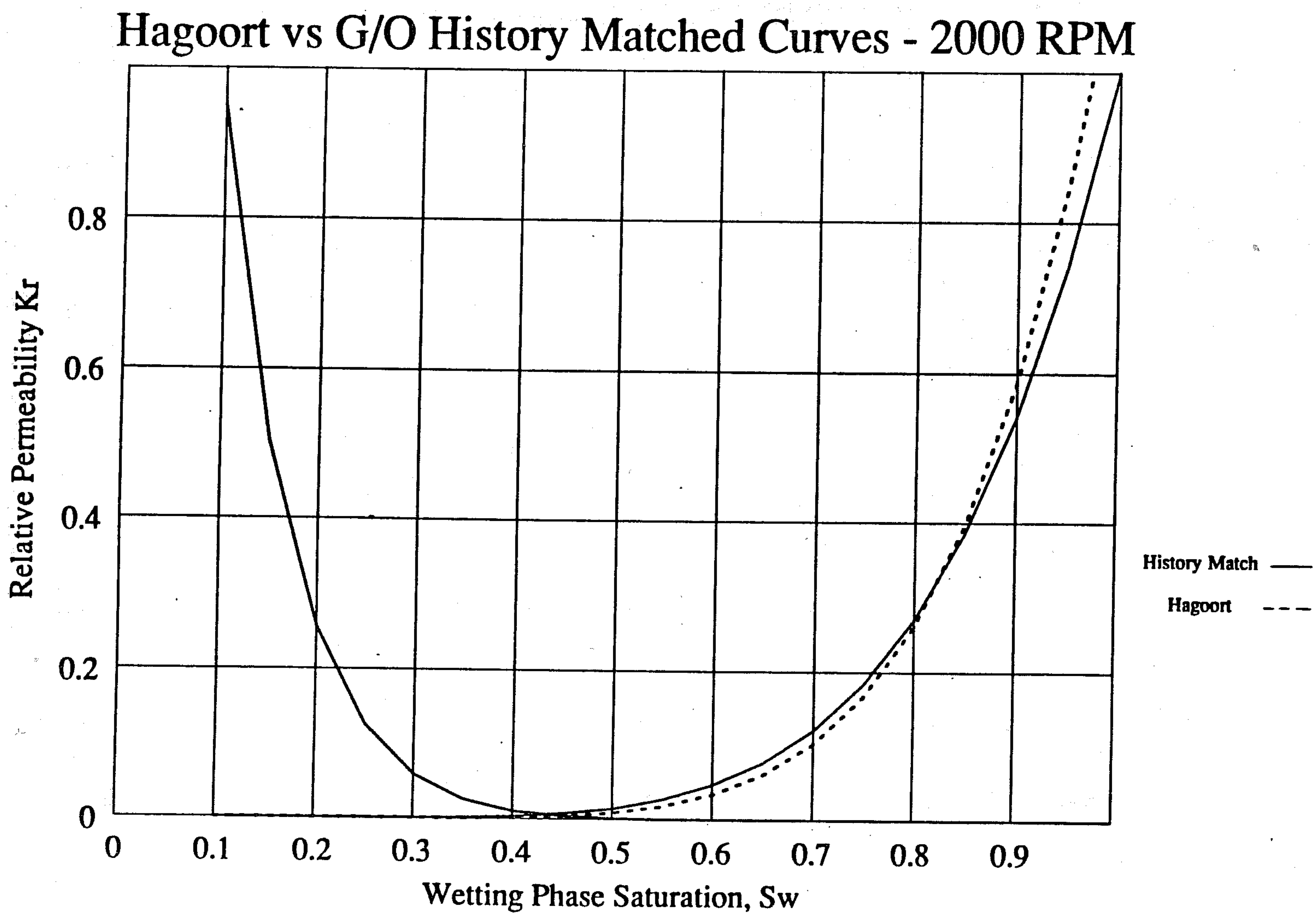

5.22 Comparison of 1000 RPM, 2000 RPM, 3000 RPM history matched curves for the gas/oil system



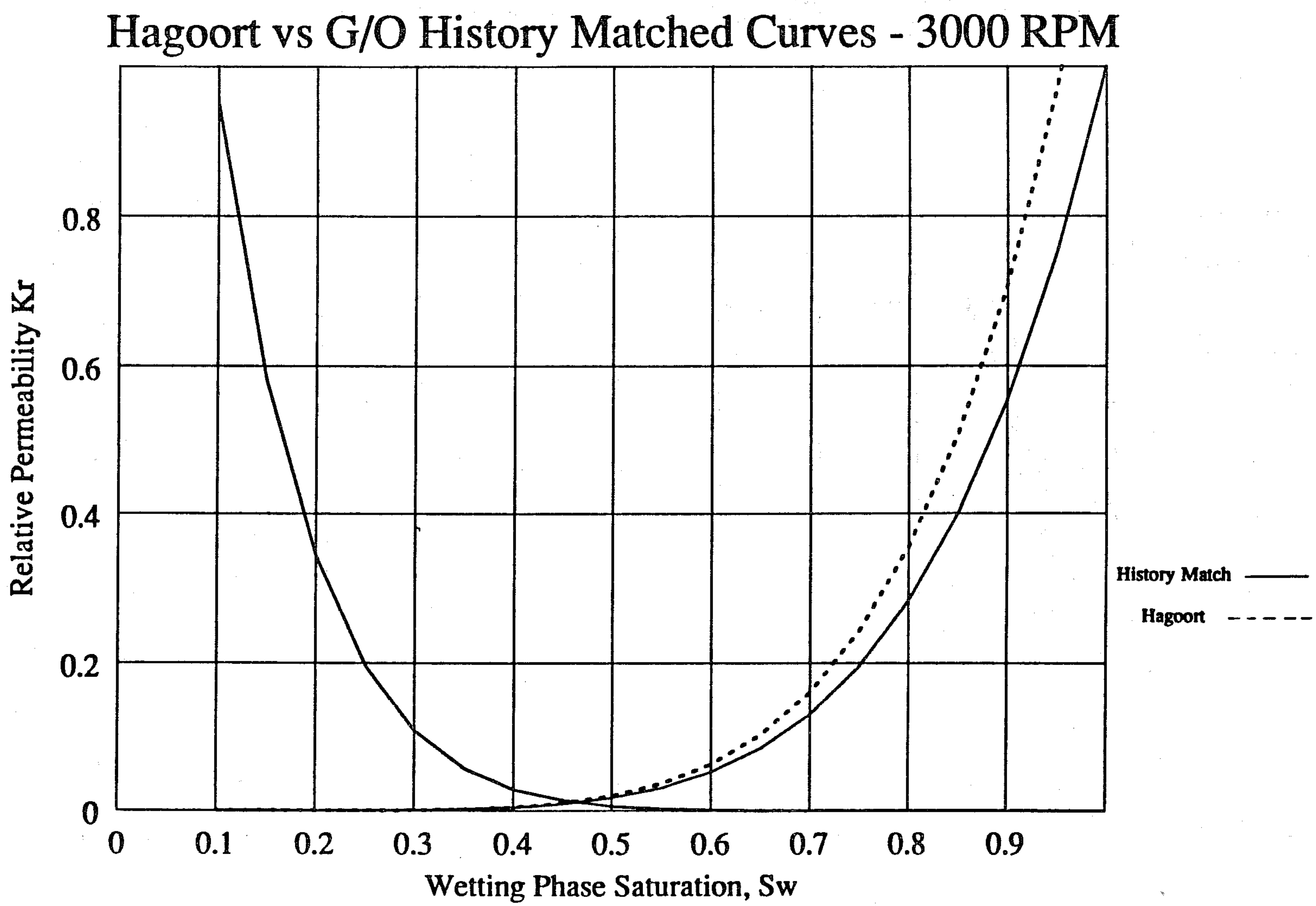

5.23 Comparison of Jones-Roszelle vs. history match curves



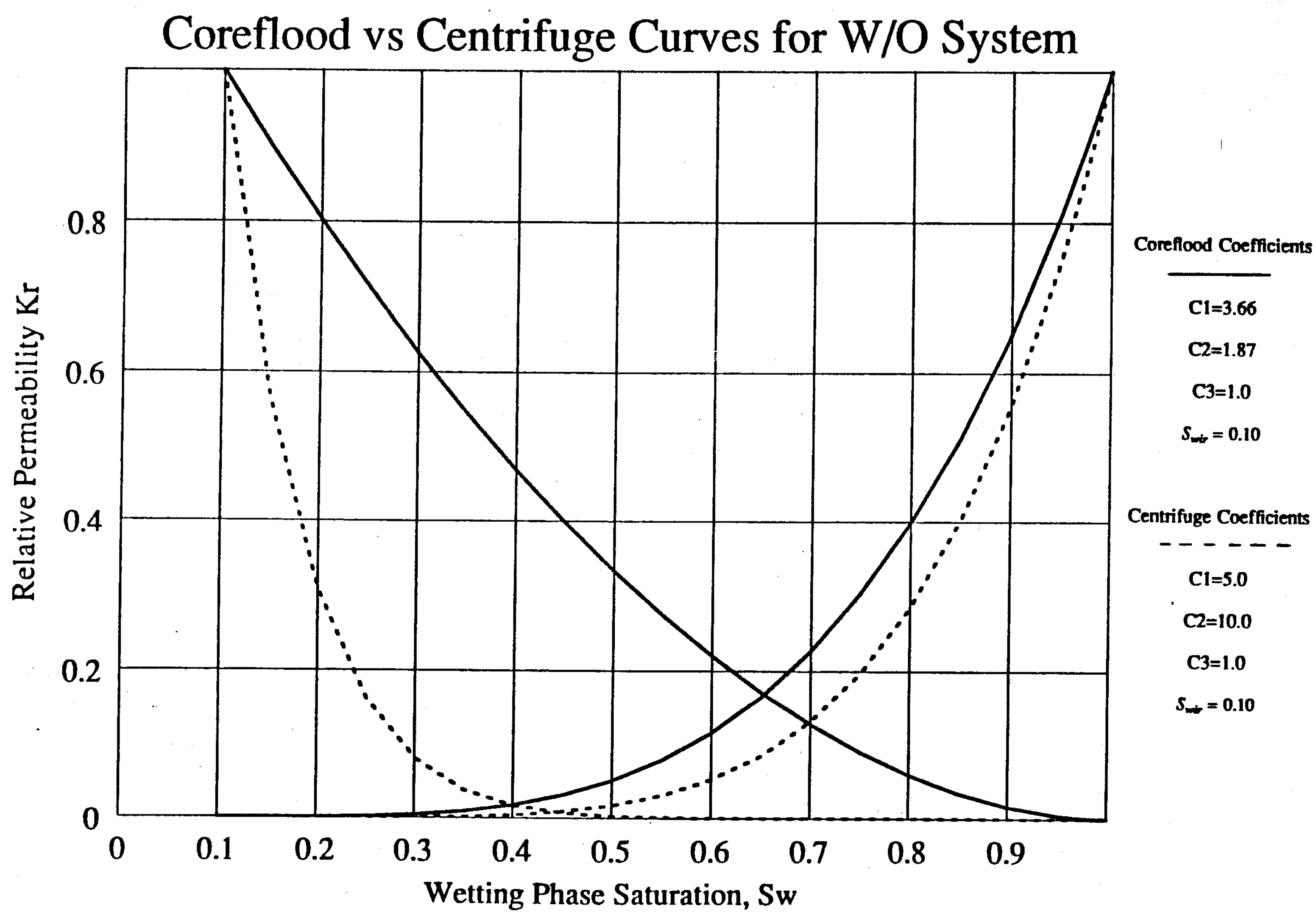

5.24 Comparison of Hagoort curves vs. history match curves for 1000 RPM




5.25 Comparison of Hagoort curves vs. history match curves for 2000 RPM




5.26 Comparison of Hagoort curves vs. history match curves for 3000 RPM




5.27 Comparison of centrifuge vs. coreflood relative permeability curves

# 6. CONCLUSIONS

1. A coreflood and a centrifuge model was derived from the same initial set of equations using different boundary conditions.

2. Coreflood and centrifuge data was obtained from the same Berea coreplug for gas/oil and oil/water systems under the drainage mode.

3. This experimental data was processed using the Jones-Roszelle graphical technique for coreflooding and Hagoort's graphical technique for centrifuging to obtain relative permeability curves.

4. A least squares history match algorithm was used to derive Corey relative permeability curves from both centrifuging and coreflooding.

5. The graphically derived Hagoort curves compared favorably with the history match curves for centrifuging.

6. The graphically derived Jones-Roszelle curves compared favorably with history match curves for coreflooding. Endpoint irreducible wetting phase saturations ($S_{wir}$) obtained from the Jones-Roszelle extrapolation technique may be too high.

7. The wetting phase curves compared favorably between coreflooding and centrifuging.

8. The nonwetting phase curves were different in both shape and irreducible wetting phase saturation endpoints ($S_{wir,coreflooding} = 0.32$, $S_{wir,centrifuging} = 0.10$) between coreflooding and centrifuging.

# 7. RECOMMENDATIONS

1. Modify the coreflood model to include pressure drop across the core in the history matching procedure. If larger timesteps are desired to reduce computer time, a more implicit solution is recommended.

2. Analyze data from other types of sandstone coreplugs to see if relative permeability relationships between coreflooding and centrifuging are consistent.

3. Run centrifuge displacement experiments at 500 and 1000 RPM. Accurately measure centrifuge speed, pressure drop across the coreplug, and production rate. Run the coreflood at an injection rate equivalent to the average centrifuge production rate, and continue running until the irreducible water saturation is comparable to the centrifuge run (if possible).

4. CATSCAN coreplugs at various times throughout the centrifuge and coreflood runs to determine saturation profiles.

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Continuity equations assuming two phase, incompressible flow:

$$\phi\frac{\partial S_{nw}}{\partial t}+\frac{\partial u_{nw}}{\partial x}=0 \tag{A.3}$$

$$\phi\frac{\partial S_{w}}{\partial t}+\frac{\partial u_{w}}{\partial x}=0 \tag{A.4}$$

Definition of capillary pressure:

$$P_c=P_{nw}-P_w \tag{A.5}$$

or, solving for $P_{nw}$:

$$P_{nw}=P_c+P_w \tag{A.6}$$

Substituting equation A.6 into equation A.1

$$u_{nw}=-k\lambda_{nw}\left[\frac{\partial P_c}{\partial x}+\frac{\partial P_w}{\partial x}-\rho_{nw}\omega_1^2R\alpha(x)\beta(t)\right] \tag{A.7}$$

Adding equation A.7 and equation A.2 and assuming $u_T=u_w+u_{nw}$ :

$$u_T=-k\lambda_{nw}\left[\frac{\partial P_c}{\partial x}+\frac{\partial P_w}{\partial x}-\rho_{nw}\omega_1^2R\alpha(x)\beta(t)\right]-k\lambda_w\left[\frac{\partial P_w}{\partial x}-\rho_w\omega_1^2R\alpha(x)\beta(t)\right] \tag{A.8}$$

Defining:

$$\lambda=\lambda_w+\lambda_{nw} \tag{A.9}$$

$$f_w=\frac{\lambda_w}{\lambda} \tag{A.10}$$

$$f_{nw}=\frac{\lambda_{nw}}{\lambda} \tag{A.11}$$

Dividing both sides by $k\lambda$ :

$$\frac{u_T}{k\lambda}=-f_{nw}\left[\frac{\partial P_c}{\partial x}+\frac{\partial P_w}{\partial x}-\rho_{nw}\omega_1^2R\alpha(x)\beta(t)\right] \tag{A.12}$$

Substituting $f_w=1-f_{nw}$

$$\frac{u_T}{k\lambda}=-f_{nw}\frac{\partial P_c}{\partial x}-\frac{\partial P_w}{\partial x}+\omega_1^2R\alpha(x)\beta(t)\left[f_{nw}\rho_{nw}-\rho_w-f_{nw}\rho_w\right]-f_w\left[\frac{\partial P_w}{\partial x}-\rho_w\omega_1^2R\alpha(x)\beta(t)\right] \tag{A.13}$$

Rearranging:

$$\frac{\partial P_w}{\partial x}=-\frac{u_T}{k\lambda}-f_{nw}\frac{\partial P_c}{\partial x}+\omega_1^2R\alpha(x)\beta(t)\left[f_{nw}\rho_{nw}+f_w\rho_w\right] \tag{A.14}$$

Substituting equation A.14 into equation A.2:

$$u_w = -k\lambda_w \left[ -\frac{u_T}{k\lambda} - f_{nw}\frac{\partial P_c}{\partial x} + \omega_1^2 R\alpha(x)\beta(t)\left[f_{nw}\rho_{nw} + f_w\rho_w\right] - \rho_w\omega_1^2 R\alpha(x)\beta(t)\right] \quad \text{(A.15)}$$

Defining $\Delta\rho = \rho_w - \rho_{nw}$ and substituting:

$$u_w = f_w\left[u_T + k\lambda_{nw}\left[\frac{\partial P_c}{\partial x} + \omega_1^2 R\alpha(x)\beta(t)\Delta\rho\right]\right] \quad \text{(A.16)}$$

Substituting into the continuity equation for the wetting phase:

$$\phi\frac{\partial S_w}{\partial t} + \frac{\partial}{\partial x}\left[f_w u_T + f_w k\lambda_{nw}\frac{\partial P_c}{\partial x} + f_w k\lambda_{nw}\omega_1^2 R\alpha(x)\beta(t)\Delta\rho\right] = 0 \quad \text{(A.17)}$$

Substituting $f_{nw}\lambda_w = f_w\lambda_{nw}$ into the second and third terms:

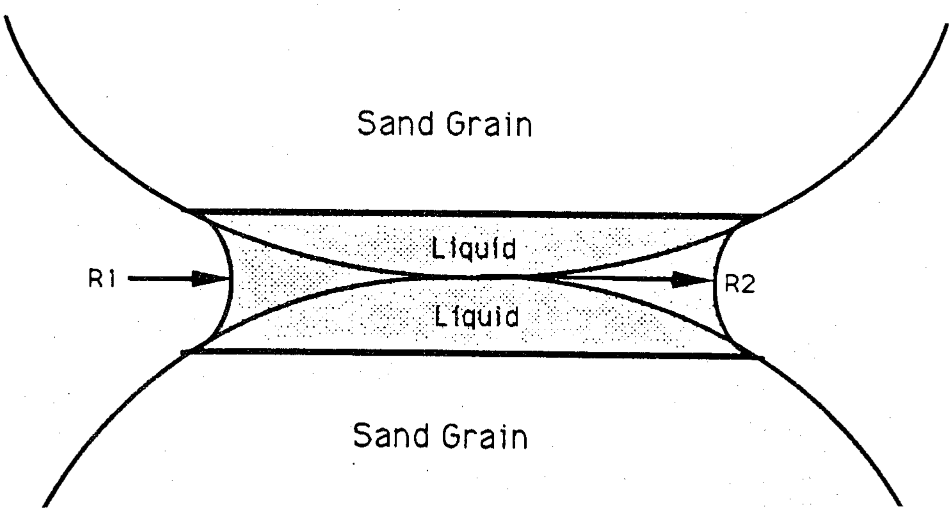
$$\phi\frac{\partial S_w}{\partial t} + \frac{\partial}{\partial x}\left[f_w u_T + kf_{nw}\lambda_w\frac{\partial P_c}{\partial x} + kf_{nw}\lambda_w\omega_1^2 R\alpha(x)\beta(t)\Delta\rho\right] = 0 \quad \text{(A.18)}$$

Boundary Conditions at the Outlet Face for Centrifuging

An important outlet face boundary condition assumption for the centrifuge model is that an infinitely small wetting phase layer exists at the outlet face of the coreplug. This allows the wetting phase saturation just inside the outlet face to be 100%.

$$S_w = 1.0 \quad \textit{at the outlet face} \quad \text{(A.19)}$$

Another boundary condition consideration is the capillary pressure. Just outside the core, it is very small relative to the capillary pressure within the pore spaces. This can be explained with the following diagram:



The capillary pressure is related to the curvature of the interface by:

$$P_c = \gamma\left[\frac{1}{R_1} + \frac{1}{R_2}\right] \tag{A.20}$$

$P_c$ = capillary pressure

$\gamma$ = interfacial tension

$R_1$ and $R_2$ = principal radii of the curvature of the interface

Capillary pressure decreases as the radius of curvature for the interfaces increases. Within the core, the capillary pressure is finite and a function of the pore throat diameter. Outside the core, the pore throat diameter (radius of curvature) becomes infinitely large, so the capillary pressure must become infinitely small. Therefore, the capillary pressure boundary condition for the outlet face is:

$$P_c = 0 \qquad \textit{at the outlet face} \tag{A.21}$$

## Boundary Conditions for the Inlet Face

If only the non-wetting phase enters the inflow end of the core, then the superficial velocity of the wetting phase ($u_w$) must equal zero at the inlet face ($x = 0$). By examining equation A.22 we can see this condition can occur in two ways:

$$u_w = f_w\left[u_T + k\lambda_{nw}\left[\frac{\partial P_c}{\partial x} + \omega_1^2 R\alpha(x)\beta(t)\Delta\rho\right]\right] = 0 \tag{A.22}$$

For this equation to be true, either $f_w = \frac{\lambda_w}{\lambda} = 0$, or the second term is equal to zero. For $f_w$ to be zero, $k_{rw}$ must equal zero. This occurs only at residual wetting phase saturation. Since inflow saturations are variable, the assumption ($f_w = 0$) is improper to use as a boundary condition.

The other inlet face boundary condition is more viable and can be defined as :

$$u_T + k\lambda_{nw}\left[\frac{\partial P_c}{\partial x} + \omega_1^2 R\alpha(x)\beta(t)\Delta\rho\right] = 0 \quad at\ x = 0 \qquad \text{(A.23)}$$

This says that the inlet face total superficial velocity is equal to the capillary pressure gradient plus a term for centrifugal acceleration. With this information a term for total superficial velocity can be derived. This total velocity is substituted into the continuity equation, and saturation at any location within the coreplug is solved for.

Total Superficial Velocity Using O'Meara and Crump's Methodology

Assuming the inlet and outlet faces of the core are immersed in the non-wetting phase, then the non-wetting phase pressure drop across the core is equal to the hydrostatic pressure drop outside the core.

$$P_{nw}(L) - P_{nw}(0) = \rho_{nw}\omega_1^2 R\beta \int_0^L \alpha(x)dx \qquad \text{(A.24)}$$

where: $\alpha(x) = 1 - \frac{L}{2R} + \frac{x}{R}$

Substituting for $\alpha(x)$ in Equation A.24 and integrating:

$$P_{nw}(L) - P_{nw}(0) = \rho_{nw}\omega_1^2 R\beta(t) \int_0^L \left[1 - \frac{L}{2R} + \frac{x}{R}\right]dx \qquad \text{(A.25)}$$

or:

$$P_{nw}(L) - P_{nw}(0) = \rho_{nw}\omega_1^2 R\beta(t)L \qquad \text{(A.26)}$$

An alternative method for obtaining the pressure gradient for the nonwetting phase uses the previously derived equation A.14 for the wetting phase:

$$\frac{\partial P_w}{\partial x} = -\frac{u_T}{k\lambda} - f_{nw}\frac{\partial P_c}{\partial x} + \omega_1^2 R\alpha(x)\beta(t)\left[f_{nw}\rho_{nw} + f_w\rho_w\right] \qquad \text{(A.27)}$$

Substituting $P_w = P_{nw} - P_c$ and $f_{nw} = 1 - f_w$ and solving for the nonwetting phase:

$$\frac{\partial(P_{nw}-P_c)}{\partial x} = -\frac{u_T}{k\lambda} - \left[1-f_w\right]\frac{\partial P_c}{\partial x} + \omega_1^2 R\alpha(x)\beta(t)\left[f_{nw}\rho_{nw} + f_w\rho_w\right] \tag{A.28}$$

Rearranging:

$$\frac{\partial P_{nw}}{\partial x} = -\frac{u_T}{k\lambda} + f_w\frac{\partial P_c}{\partial x} + \omega_1^2 R\alpha(x)\beta(t)\left[f_{nw}\rho_{nw} + f_w\rho_w\right] \tag{A.29}$$

Integrating with respect to x :

$$P_{nw}(L) - P_{nw}(0) = \int_0^L -\frac{u_T}{k\lambda}dx + \int_0^L f_w\frac{\partial P_c}{\partial x}dx + \omega_1^2 R\beta(t)\int_0^L \left[\rho_{nw}f_{nw} + \rho_w f_w\right]\alpha(x)dx \tag{A.30}$$

Equating equation A.24 and equation A.30 :

$$\rho_{nw}\omega_1^2 R\beta\int_0^L \alpha(x)dx = \int_0^L -f_w\frac{\partial P_c}{\partial x}dx + \omega_1^2 R\beta\int_0^L \left[\rho_{nw}f_{nw} + \rho_w f_w\right]\alpha(x)dx \tag{A.31}$$

Rearranging and solving for the total velocity ($u_T$):

$$\int_0^L \frac{u_T}{k\lambda}dx = \int_0^L f_w\frac{\partial P_c}{\partial x}dx + \omega_1^2 R\beta(t)\int_0^L \left[\rho_{nw}f_{nw} + \rho_w f_w - \rho_{nw}\right]\alpha(x)dx \tag{A.32}$$

Substituting $f_{nw} = 1 - f_w$ and $\Delta\rho = \rho_w - \rho_{nw}$, a term for total velocity ($u_T$) can be derived:

$$u_T = \frac{\int_0^L f_w\frac{\partial P_c}{\partial x}dx + \omega_1^2 R\beta(t)\int_0^L f_w\Delta\rho\alpha(x)dx}{\int_0^L \frac{dx}{k\lambda}} \tag{A.33}$$

This integration problem is solved numerically using the trapezoidal rule.

<u>Discretization of Flow Equations for Centrifuging</u>

Beginning with the continuity equation for the non-wetting phase:

$$\phi\frac{\partial S_w}{\partial t} + \frac{\partial u_w}{\partial x} = 0 \tag{A.34}$$

Using the first order forward difference approximation:

$$\frac{\partial S_w}{\partial t} = \frac{(S_{wi}^{n+1} - S_{wi}^{n})}{\Delta t} \tag{A.35}$$

Evaluating the velocity term using the central difference method:

$$u_w = f_w\left[u_t + k\lambda_{nw}\left[\frac{\partial P_c}{\partial x} + \Delta\rho\omega_1^2 R\alpha(x)\beta(t)\right]\right] \tag{A.36}$$

Taking the derivative and discretizing:

$$\frac{\partial u_w}{\partial x} = \left[\frac{f_{w,i+\frac{1}{2}} - f_{w,i-\frac{1}{2}}}{\Delta x}\right]u_t + \frac{1}{\Delta x}\left[\left[k\lambda_{nw}f_w\right]_{i+\frac{1}{2}}\left[\frac{P_{c,i+1} - P_{c,i}}{\Delta x}\right] + \left[k\lambda_{nw}f_w\right]_{i-\frac{1}{2}}\left[\frac{P_{c,i-1} - P_{c,i}}{\Delta x}\right]\right] +$$
$$\frac{1}{\Delta x}\left[\left[k\lambda_{nw}f_w\Delta\rho\omega_1^2 R\alpha(x)\beta(t)\right]_{i+\frac{1}{2}} - \left[k\lambda_{nw}f_w\Delta\rho\omega_1^2 R\alpha(x)\beta(t)\right]_{i-\frac{1}{2}}\right] \tag{A.37}$$

Using upstream weighting:

$$\left[\lambda_{nw}f_w\right]_{i+\frac{1}{2}} = f\left[S_{wi}\right] \tag{A.38}$$

$$\left[\lambda_{nw}f_w\right]_{i-\frac{1}{2}} = f\left[S_{w,i-1}\right] \tag{A.39}$$

Substituting the discretized form of the velocity term and saturation term into the continuity equation:

$$S_{wi}^{n+1} = S_{wi}^{n} - \frac{\Delta t}{\Delta x\phi}\left[f_{w,i+\frac{1}{2}} - f_{w,i-\frac{1}{2}}\right]^n u_t - \frac{\Delta t}{\Delta x\phi}\left[\left[k\lambda_{nw}f_w\right]_{i+\frac{1}{2}}\left[\frac{P_{c,i+1} - P_{c,i}}{\Delta x}\right] + \left[k\lambda_{nw}f_w\right]_{i-\frac{1}{2}}\left[\frac{P_{c,i-1} - P_{c,i}}{\Delta x}\right]\right]^n -$$
$$\frac{\Delta t}{\phi\Delta x}\left[\left[k\lambda_{nw}f_w\Delta\rho\omega_1^2 R\alpha(x)\beta(t)\right]_{i+\frac{1}{2}} - \left[k\lambda_{nw}f_w\Delta\rho\omega_1^2 R\alpha(x)\beta(t)\right]_{i-\frac{1}{2}}\right]^n \tag{A.40}$$

This explicit solution to the saturation equation is used in the centrifuge model.

# APPENDIX B

## DERIVATION OF FLOW EQUATIONS FOR COREFLOODING

Flow equations for the coreflood model can be obtained by simplifying the previously derived centrifuge equations. Beginning with Equation A.16 and dropping the centrigugal gravity term:

$$u_w = f_w u_T + \lambda_w k f_{nw} \frac{\partial P_c}{\partial x} = f_w \left[ u_T + k \lambda_{nw} \frac{\partial P_c}{\partial x} \right] \tag{B.1}$$

Substituting into the continuity equation:

$$\phi \frac{\partial S_w}{\partial t} + \frac{\partial}{\partial x} \left[ f_w u_T + f_w k \lambda_{nw} \frac{\partial P_c}{\partial x} \right] = 0 \tag{B.2}$$

Defining capillary pressure:

$$P_c = P_{nw} - P_w \tag{B.3}$$

or, taking the derivative:

$$\frac{\partial P_c}{\partial x} = \frac{\partial P_{nw}}{\partial x} - \frac{\partial P_w}{\partial x} \tag{B.4}$$

For a two phase system:

$$S_w + S_{nw} = 1 \tag{B.5}$$

or, taking the derivative:

$$\frac{\partial S_w}{\partial t} + \frac{\partial S_{nw}}{\partial t} = 0 \tag{B.6}$$

$$\frac{\partial S_w}{\partial t} = \frac{\partial S_w}{\partial P_c} \frac{\partial P_c}{\partial t} = \frac{\partial S_w}{\partial P_c} \left[ \frac{\partial P_{nw}}{\partial t} - \frac{\partial P_w}{\partial t} \right] \tag{B.7}$$

Substituting equations B.4 and equations B.7 into equation B.2:

$$\phi\frac{\partial S_w}{\partial P_c}\left[\frac{\partial P_{nw}}{\partial t}-\frac{\partial P_w}{\partial t}\right]+\frac{\partial}{\partial x}\left[f_w u_t+f_w k\lambda_{nw}\left[\frac{\partial P_{nw}}{\partial x}\right]\right]=0 \qquad \text{(B.8)}$$

Boundary Conditions at the Inlet Face for Coreflooding

The injection point at the inlet face of the coreplug is defined as a constant rate injector.

$$u_{nw}(x=0,t) \;=\; \textit{constant rate } \text{for } \textit{the nonwetting phase} \qquad \text{(B.9)}$$

Boundary Conditions at the Outlet Face for Coreflooding

$$P_c = 0 \qquad \textit{at the outlet face after breakthrough} \qquad \text{(B.10)}$$

See discussion of centrifuge outlet face boundary conditions for more detailed explanation.

$$P_w(x=L,t) \;=\; \textit{constant pressure at the outlet face} \qquad \text{(B.11)}$$

Before breakthrough, assuming an incompressible fluid, the nonwetting phase injection rate at the inlet face equals the wetting phase rate at the outlet face.

$$u_{nw}(x=0,t) \;=\; u_w(x=L,t) \qquad \text{(B.12)}$$

After breakthrough, the nonwetting phase injection rate at the inlet face equals the nonwetting phase exit rate plus the wetting phase exit rate.

$$u_{nw}(x=0,t) \;=\; u_{nw}(x=l,t)+u_w(x=L,t) \qquad \text{(B.13)}$$

Discretization of Flow Equations for Coreflooding

Beginning with the continuity equation for the wetting phase:

$$\phi\frac{\partial S_w}{\partial t}+\frac{\partial u_w}{\partial x}=0 \qquad \text{(B.14)}$$

Using the first order forward difference approximation:

$$\frac{\partial S_w}{\partial t} = \frac{1}{\Delta t}\left[S_{wi}^{n+1} - S_{wi}^{n}\right] \tag{B.15}$$

Evaluating the velocity term in equation B.1

$$u_w = f_w\left[u_T + k\lambda_{nw}\frac{\partial P_c}{\partial x}\right] \tag{B.16}$$

Taking the derivative of the velocity term and discretizing using the central difference method:

$$\frac{\partial u_w}{\partial x} = \left[\frac{f_{w,i+\frac{1}{2}} - f_{w,i-\frac{1}{2}}}{\Delta x}\right]u_T + \frac{1}{\Delta x}\left[(k\lambda_{nw}f_w)_{i+\frac{1}{2}}\left[\frac{P_{c,i+1} - P_{c,i}}{\Delta x}\right] + (k\lambda_{nw}f_w)_{i-\frac{1}{2}}\left[\frac{P_{c,i-1} - P_{c,i}}{\Delta x}\right]\right] \tag{B.17}$$

Using upstream weighting:

$$(\lambda_{nw}f_w)_{i+\frac{1}{2}} = f(S_{wi}) \tag{B.18}$$

$$(\lambda_{nw}f_w)_{i-\frac{1}{2}} = f(S_{w,i-1}) \tag{B.19}$$

Substituting equations B.15 and B.17 into the continuity equation B.14:

$$S_{wi}^{n+1} = S_{wi}^{n} - \frac{\Delta t}{\Delta x\phi}\left[f_{w,i+\frac{1}{2}} - f_{w,i-\frac{1}{2}}\right]^n u_T - \frac{\Delta t}{\Delta x\phi}\left[k\lambda_{nw}f_w\right]_{i+\frac{1}{2}}\left[\frac{P_{c,i+1} - P_{ci}}{\Delta x}\right]^n - \frac{\Delta t}{\Delta x\phi}\left[k\lambda_{nw}f_w\right]_{i-\frac{1}{2}}\left[\frac{P_{c,i-1} - P_{ci}}{\Delta x}\right]^n$$

This solution to the saturation equation is used in the coreflood model.

## Discretized Boundary Conditions for Coreflooding

Before nonwetting phase breakthrough at x = L for outlet block i:

$$u_{nwi} = 0 \tag{B.21}$$

$$u_{wi} = \frac{q_{inj}}{A} \tag{B.22}$$

where: $q_{inj}$ = injection rate

A = cross sectional area

$u_{wi}$ = wetting phase velocity at outlet face

$u_{nwi}$ = nonwetting phase velocity at outlet face

Discretizing the continuity equation using a one-sided difference method for the velocity term:

$$\frac{\phi}{\Delta t}\left[S_{nwi}^{n+1} - S_{nwi}^{n}\right] + \frac{1}{\Delta x}\left[u_{nwi}^{n} - u_{nw,i-1}^{n}\right] = 0 \tag{B.23}$$

Since $u_{nwi} = 0$, the new outlet face function becomes:

$$0 = \phi\Delta x\left[S_{nwi}^{n+1} - S_{nwi}^{n}\right] - \Delta t\left[u_{nw,i-1}^{n}\right] \tag{B.24}$$

From equation B.16:

$$u_{nw,i-1} = f_{nw,i-\frac{1}{2}}\, u_T + (k\lambda_w f_{nw})_{i-\frac{1}{2}}\left[\frac{P_{c,i-1} - P_{ci}}{\Delta x}\right] \tag{B.25}$$

Substituting equation B.25 into equation B.24 and solving for saturation:

$$S_{nwi}^{n+1} = S_{nwi}^{n} + \frac{\Delta t}{\Delta x\phi}(f_{nw})_{i-\frac{1}{2}}^{n}\, u_T + \frac{\Delta t}{\Delta x\phi}(k\lambda_w f_{nw})_{i-\frac{1}{2}}^{n}\left[\frac{P_{c,i-1} - P_{ci}}{\Delta x}\right]^{n} \tag{B.26}$$

This saturation is solved explicitly in the model.

# APPENDIX C

## Derivation of Equations for Least Squares History Matching Algorithm Using Firoozabadi-Aziz Methodology

$$\sum_{j=1}^{m}\sum_{k=1}^{N} w_j \left[\frac{\partial R_j^{calc}}{\partial x_k}\right]\left[\frac{\partial R_j^{calc}}{\partial x_h}\right]\Delta x_k = \sum_{j=1}^{m} w_j \Delta R_j^0 \frac{\partial R_j^{calc}}{\partial x_h} \qquad h = 1, n \qquad \text{(C.1)}$$

where $R_j^{calc} = R_j^{0calc} + \sum_{j=1}^{m} w \frac{\partial R_j^{calc}}{\partial x_k}\Delta x_k$

$\Delta R_j^0 = R_j^{obs} - R_j^{0calc}$

$R_{obs}$ = observed recovery

$R_{calc}$ = calculated recovery for $x_k + \Delta x_k$

$R_{0calc}$ = calculated recovery for $x_k$

$m$ = number of recovery observations to be history matched

$N$ = number of Corey coefficients = 3

$w_j$ = weight factor for history match data

$\Delta x_k$ = increment factor for Corey coefficients

## Matrix Form of Least Squares History Matching Algorithm

$$\begin{bmatrix}
\sum_{j=1}^{m} w_j \left[\frac{\partial R_j}{\partial x_1}\right]\left[\frac{\partial R_j}{\partial x_1}\right] & \sum_{j=1}^{m} w_j \left[\frac{\partial R_j}{\partial x_2}\right]\left[\frac{\partial R_j}{\partial x_1}\right] & \sum_{j=1}^{m} w_j \left[\frac{\partial R_j}{\partial x_3}\right]\left[\frac{\partial R_j}{\partial x_1}\right] \\
\sum_{j=1}^{m} w_j \left[\frac{\partial R_j}{\partial x_1}\right]\left[\frac{\partial R_j}{\partial x_2}\right] & \sum_{j=1}^{m} w_j \left[\frac{\partial R_j}{\partial x_2}\right]\left[\frac{\partial R_j}{\partial x_2}\right] & \sum_{j=1}^{m} w_j \left[\frac{\partial R_j}{\partial x_3}\right]\left[\frac{\partial R_j}{\partial x_2}\right] \\
\sum_{j=1}^{m} w_j \left[\frac{\partial R_j}{\partial x_1}\right]\left[\frac{\partial R_j}{\partial x_3}\right] & \sum_{j=1}^{m} w_j \left[\frac{\partial R_j}{\partial x_2}\right]\left[\frac{\partial R_j}{\partial x_3}\right] & \sum_{j=1}^{m} w_j \left[\frac{\partial R_j}{\partial x_3}\right]\left[\frac{\partial R_j}{\partial x_3}\right]
\end{bmatrix}
\begin{bmatrix} \Delta x_1 \\ \Delta x_2 \\ \Delta x_3 \end{bmatrix}
\begin{bmatrix}
\sum_{j=1}^{m} w_j \Delta R_j^0 \frac{\partial R_j^{calc}}{\partial x_1} \\
\sum_{j=1}^{m} w_j \Delta R_j^0 \frac{\partial R_j^{calc}}{\partial x_2} \\
\sum_{j=1}^{m} w_j \Delta R_j^0 \frac{\partial R_j^{calc}}{\partial x_3}
\end{bmatrix}$$

# Appendix D.1 - Coreflood Model

```
      implicit real*8(a-h,o-z)
      dimension x(100),sw(100),sn(100),fw(100),pc(100)
      dimension snold(100),swold(100)
      dimension fn(100),flamn(100),flamw(100),flamt(100)
c
c     COREFLOOD MODEL (DRAINAGE) WITH COREY RELATIVE PERMEABILITY CURVES
c
      open(11,file='timepvcore',access='sequential')
      rewind(11)
      open(12,file='mbcore',access='sequential')
      rewind(12)
      open(14,file='swcore',access='sequential')
      rewind(14)
c
c     Read in constant parameters
c
      print *,'Input POROSITY (fraction), PERMEABILITY (Darcys)'
      read(5,*)phi,perm
      print *,'Input NON-WETTING VISCOSITY (cp), WETTING VISCOSITY (cp)'
      read(5,*)viscn,viscw
      print*,'Input FLUID DENSITY DIFFERENCE BETWEEN TWO PHASES (g/cc)'
      read(5,*)drho
      print *,'Input COREPLUG LENGTH (cm), X-SEC AREA (sq. cm.)'
      read(5,*)cplength,area
      print *,'Input INJECTION RATE (cm/sec)'
      read(5,*)qinj
      print *,'TIMESTEP SIZE (sec), TEND (sec), NUMBER OF MODEL CELLS'
      read(5,*)dt,tend,ncells
      dx=cplength/dfloat(ncells)
      print*,'Input CAP PRESSURE COEFFICIENT, ENTRY PRESSURE (atm)'
      read(5,*)sig,pe
c
c     Initialize arrays
c
c     For drainage coreflooding, the sample is initially 100% saturated
c     with the wetting phase and is displaced by the non-wetting phase
c
      do 1 i=1,ncells
      x(i)=dx/2.d0+dfloat(i-1)*dx
      sw(i)=1.0d0
      sn(i)=0.0d0
      pc(i)=0.0d0
    1 continue
      beta=1.0d0
      porvol=0.0d0
      pvw=0.d0
      pvnw=0.d0
      time=0.0d0
      nstep=0
      cumnprod=0.d0
      cumwprod=0.d0
c
c     Calculate mobilities (flamn,flamw,flamt) and fractional flow (fw,fn)
c     using the Corey relative permeability relationship
c            corey1 = exponential factor for wetting phase
c            corey2 = exponential factor for non-wetting phase
c            corey3 = relative permeability factor for non-wetting phase
c            swc = connate water saturation
c            akrwi = wetting phase relative permeability
c            akrni = non-wetting phase relative permeability
c
      print*,'Input constants and coefficients for Corey relative perme
     &ability'
      print*,'  '
      print*,'COREY1 = exponential factor for wetting phase'
      print*,'COREY2 = exponential factor for non-wetting phase'
```

```
      print*,'COREY3 = relative permeability factor for non-wetting pha
     &se'
      print*,'Swc = connate water saturation'
      print*,'  '
      print*,'Input COREY1, COREY2, COREY3'
      read(5,*)corey1,corey2,corey3
      print*,'Input connate water saturation, Swc'
      read(5,*)swc
c
c     Calculate mobilities (flamn,flamw,flamt) and fractional flow (fw,fn)
c     using the Corey relative permeability relationship
c
      do 44 i=1,ncells
      temp=((sw(i)-swc)/(1.d0-swc))
      if(temp.le.0.d0)then
      temp=0.d0
      sw(i)=swc
      endif
      akrwi=temp**corey1
      temp1=(1.d0-(sw(i)-swc)/(1.d0-swc))
      if(temp1.le.0.d0)then
      temp1=0.d0
      sw(i)=1.d0
      endif
      akrni=corey3*(temp1**corey2)
      flamn(i)=akrni/viscn
      flamw(i)=akrwi/viscw
      flamt(i)=flamn(i)+flamw(i)
      fw(i)=flamw(i)/flamt(i)
      fn(i)=flamn(i)/flamt(i)
      sn(i)=1.d0-sw(i)
   44 continue
c
c     Calculate Capillary Pressure Data
c     Using Log Function
c
      do 99 i=1,ncells
      temp2=(sw(i)-swc)/(1.0d0-swc)
      if(temp2.le.0.d0)then
      temp2=.0001
      sw(i)=swc
      endif
      pc(i)=-sig*log(temp2)+pe
      if(pc(i).eq.pe)then
      pc(i)=0.d0
      endif
      if(sn(i).lt.0.d0)then
      pc(i)=0.d0
      endif
   99 continue
c
c     Calculate initial velocity
c
      ut=qinj/area
c      print*,'INITIAL VELOCITY = ',ut
c
c     Calculate change in saturation for first cell from injection
c     using source term ut
c
      sw(1)=sw(1)-(dt*ut)/(phi*dx*0.5d0)-(perm*dt)/(phi*dx*0.5d0)*
     &    (flamn(1)*fw(1)*(pc(2)-pc(1))/dx)
c
c     Begin stepping forward in time
c
    2 time=time+dt
      nstep=nstep+1
```

```
c
c     Calculate mobilities (flamn,flamw,flamt) and fractional flow (fw,fn)
c     using the Corey relative permeability relationship
c
      do 4 i=1,ncells
      temp3=((sw(i)-swc)/(1.d0-swc))
      if(temp3.le.0.d0)then
      temp3=0.d0
      sw(i)=swc
      endif
      akrwi=temp3**corey1
      temp4=(1.d0-(sw(i)-swc)/(1.d0-swc))
      if(temp4.le.0.d0)then
      temp4=0.d0
      sw(i)=1.d0
      endif
      akrni=corey3*(temp4**corey2)
      flamn(i)=akrni/viscn
      flamw(i)=akrwi/viscw
      flamt(i)=flamn(i)+flamw(i)
      fw(i)=flamw(i)/flamt(i)
      fn(i)=flamn(i)/flamt(i)
      sn(i)=1.d0-sw(i)
    4 continue
c
c     Calculate Capillary Pressure Data
c     Using Log Function
c
      do 88 i=1,ncells
      temp5=(sw(i)-swc)/(1.0d0-swc)
      if(temp5.le.0.d0)then
      temp5=.0001
      sw(i)=swc
      endif
      pc(i)=-sig*log(temp5)+pe
      if(pc(i).eq.pe)then
      pc(i)=0.d0
      endif
      if(sn(i).lt.0.d0)then
      pc(i)=0.d0
      endif
   88 continue
      pc(ncells)=0.d0
c
c     For coreflooding, total velocity is constant
c
c
c     Increase timestep size if time > 100
c
      if(nstep.eq.200)dt=1.0d0
c
c     Increase timestep size if time > 1000
c
      if(nstep.eq.1100)dt=2.0
      do 9 j=1,ncells
      snold(j)=sn(j)
      swold(j)=sw(j)
    9 continue
c
c     Solve saturation equations explicitly
c
      sw(1)=sw(1)-(dt/(phi*dx*0.5d0))*(fw(1)*ut+perm*flamn(1)*fw(1)*
     &  (pc(2)-pc(1))/dx)
      do 6 i=2,ncells
      sw(i)=sw(i)-(dt/(phi*dx))*((fw(i)-fw(i-1))*ut+perm*flamn(i)*
     &   fw(i)*(pc(i+1)-pc(i))/dx+perm*flamn(i-1)*fw(i-1)*
```

```
     &    (pc(i-1)-pc(i))/dx)
    6 continue
c
c     Outlet face cell water saturation always equals 1.0
c     if capillary pressure is included
c
      if(sig.eq.0.d0)go to 16
      sw(ncells)=1.0d0
   16 continue
c
c     Outlet face boundary condition
c     Production from the core is determined using fractional flows
c     coming out of cell (ncells-1)
c
      uw39=fw(ncells-1)*(ut+perm*flamn(ncells-1)*
     &    (pc(ncells)-pc(ncells-1))/dx)
      qwprod=uw39*area
      qnprod=qinj-qwprod
c
c     Calculate wetting phase pore volume produced
c
      porvol=porvol+qwprod*dt/(cplength*area*phi)
c
c     Material balance check for wetting and non-wetting phases
c
      recmbl=0.0
      do 8 i=1,ncells-2
      recmbl=recmbl+sw(i+1)
    8 continue
      recmb=(1./(ncells-1))*(2.*recmbl+sw(1)+sw(ncells))*0.5
      recmb=1.-recmb
      recsnl=0.0
      do 80 i=1,ncells-2
      recsnl=recsnl+sn(i+1)
   80 continue
      recsn=(1./(ncells-1))*(2.*recsnl+sn(1)+sn(ncells))*0.5
c
c     Print results and go back to next timestep
c
      cumwprod=cumwprod+qwprod*dt
      cumnwprod=cumnwprod+qnprod*dt
      weght=1.0
      write(11,*)time,recmb
c      write(12,*)'time   porvol  ',time,recmb
c      write(12,*)'mbsw  mbsn  ',recmb,recsn
c      write(6,100)nstep,time,recmb,qwprod,qnprod
c  100 format(/,' step ',i7,' Time ',f11.5,' PV ',f6.5,
c     & ' Water ',f10.7,' Oil ',f10.7)
c      if(nstep.eq.1)then
c      write(14,*)nstep,time,porvol,qwprod,qnprod
c      do 101 i=1,ncells
c      write(14,*)x(i),sw(i),pc(i)
c  101 continue
c      endif
c      if(nstep.eq.100)then
c      write(14,*)nstep,time,porvol,qwprod,qnprod
c      do 98 i=1,ncells
c      write(14,*)x(i),sw(i),pc(i)
c   98 continue
c      endif
c      if(nstep.eq.1000)then
c      write(14,*)nstep,time,porvol,qwprod,qnprod
c      do 102 i=1,ncells
c      write(14,*)x(i),sw(i),pc(i)
c  102 continue
c      endif
```

```
c       if(nstep.eq.2000)then
c       write(14,*)nstep,time,porvol,qwprod,qnprod
c       do 103 i=1,ncells
c       write(14,*)x(i),sw(i),pc(i)
c  103  continue
c       endif
c       if(nstep.eq.5000)then
c       write(14,*)nstep,time,porvol,qwprod,qnprod
c       do 105 i=1,ncells
c       write(14,*)x(i),sw(i),pc(i)
c  105  continue
c       endif
       if(time.le.tend)go to 2
c       write(14,*)nstep,time,porvol,qwprod,qnprod
c       do 104 i=1,ncells
c       write(14,*)x(i),sw(i),pc(i)
c  104  continue
       close(10)
       close(11)
       close(14)
       close(12)
       stop
       end
```

## Appendix D.2 - Coreflood Model with Least Squares History Matching

```
      implicit real*8(a-h,o-z)
      dimension x(100),sw(100),sn(100),fw(100),pc(100)
      dimension snold(100),swold(100)
      dimension fn(100),flamn(100),flamw(100),flamt(100)
      dimension timo(1000),obrec(1000),erc(1000),calcrec(1000),
     &  calcreco(1000),ddobrec(1000),drecw(1000),drecn(1000),
     & dreck(1000),calcrecw(1000),
     & calcrecn(1000),calcreck(1000),
     & weght(1000)
c
c     COREFLOOD MODEL WITH COREY RELATIVE PERMEABILITY CURVES
c     HISTORY MATCHING ALGORITM USING LEAST SQUARES
c
      open(7,file='hmdatacoreba2',access='sequential')
      rewind(7)
      open(11,file='timepvcore',access='sequential')
      rewind(11)
      open(12,file='mbcore',access='sequential')
      rewind(12)
      open(67,file='itercoreba2',access='sequential')
      rewind(67)
      open(14,file='swcore',access='sequential')
      rewind(14)
c
c     Read in constant parameters
c
      print *,'Input POROSITY (fraction), PERMEABILITY (Darcys)'
      read(5,*)phi,perm
      print *,'Input NON-WETTING VISCOSITY (cp), WETTING VISCOSITY (cp)'
      read(5,*)viscn,viscw
      print*,'Input FLUID DENSITY DIFFERENCE BETWEEN TWO PHASES (g/cc)'
      read(5,*)drho
      print *,'Input COREPLUG LENGTH (cm), X-SEC AREA (sq. cm.)'
      read(5,*)cplength,area
      print *,'Input INJECTION RATE (cm/sec)'
      read(5,*)qinj
      print *,'TIMESTEP SIZE (sec), TEND (sec), NUMBER OF MODEL CELLS'
      read(5,*)dt,tend,ncells
      dtinit=dt
      dx=cplength/dfloat(ncells)
      print*,'Input CAP PRESSURE COEFFICIENT, ENTRY PRESSURE (atm)'
      read(5,*)sig,pe
c
c     Calculate mobilities (flamn,flamw,flamt) and fractional flow (fw,fn)
c     using the Corey relative permeability relationship
c           corey1 = exponential factor for wetting phase
c           corey2 = exponential factor for non-wetting phase
c           corey3 = relative permeability factor for non-wetting phase
c           swc = connate water saturation
c           akrwi = wetting phase relative permeability
c           akrni = non-wetting phase relative permeability
c
      print*,'Input constants and coefficients for Corey relative permea
     &bility'
      print*,'  '
      print*,'COREY1 = exponential factor for wetting phase'
      print*,'COREY2 = exponential factor for non-wetting phase'
      print*,'COREY3 = relative permeability factor for non-wetting phas
     &e'
      print*,'Swc = connate water saturation'
      print*,'  '
      print*,'Input COREY1, COREY2, COREY3'
      read(5,*)corey1,corey2,corey3
      print*,'Input connate water saturation, Swc'
      read(5,*)swc
c
```

```
c     Read history match recovery data
c
      read(7,*)nobs,dcorey,toll
      read(7,*)(j,timo(j),obrec(j),weght(j),j=1,nobs)
c
c     Initialize arrays
c
c     For drainage coreflooding, the sample is initially 100% saturated
c     with the wetting phase and is displaced by the non-wetting phase
c
      k=1
      kkk=1
      iter=0
  999 continue
      do 1 i=1,ncells
      x(i)=dx/2.d0+dfloat(i-1)*dx
      sw(i)=1.0d0
      sn(i)=0.0d0
      pc(i)=0.0d0
    1 continue
      beta=1.0d0
      porvol=0.0d0
      pvw=0.d0
      pvnw=0.d0
      time=0.0d0
      nstep=0
      dt=dtinit
c
c     Calculate mobilities (flamn,flamw,flamt) and fractional flow (fw,fn)
c     using the Corey relative permeability relationship
c
      do 44 i=1,ncells
      temp=((sw(i)-swc)/(1.d0-swc))
      if(temp.lt.0.d0)then
      temp=0.d0
      sw(i)=swc
      endif
      akrwi=temp**corey1
      temp1=(1.d0-(sw(i)-swc)/(1.d0-swc))
      if(temp1.lt.0.d0)then
      temp1=0.d0
      sw(i)=1.0d0
      endif
      akrni=corey3*(temp1**corey2)
      flamn(i)=akrni/viscn
      flamw(i)=akrwi/viscw
      flamt(i)=flamn(i)+flamw(i)
      fw(i)=flamw(i)/flamt(i)
      fn(i)=flamn(i)/flamt(i)
      sn(i)=1.d0-sw(i)
   44 continue
c
c     Calculate Capillary Pressure Data
c     Using Log Function
c
      do 99 i=1,ncells
      temp2=(sw(i)-swc)/(1.d0-swc)
      if(temp2.le.0.d0)then
      temp2=.0001
      sw(i)=swc
      endif
      pc(i)=-sig*log(temp2)+pe
      if(pc(i).eq.pe)then
      pc(i)=0.d0
      endif
   99 continue
```

```
c
c     Calculate initial velocity
c
      ut=qinj/area
c      print*,'INITIAL VELOCITY = ',ut
c
c     Calculate change in saturation for first cell from injection
c     using source term ut
c
      sw(1)=sw(1)-(dt*ut)/(phi*dx*0.5d0)-(perm*dt)/(phi*dx*0.5d0)*
     &   (flamn(1)*fw(1)*(pc(2)-pc(1))/dx)
c
c     Begin stepping forward in time
c
    2 continue
      time=time+dt
      nstep=nstep+1
c
c     Calculate mobilities (flamn,flamw,flamt) and fractional flow (fw,fn)
c     using the Corey relative permeability relationship
c
      do 4 i=1,ncells
      temp3=((sw(i)-swc)/(1.d0-swc))
      if(temp3.lt.0.d0)then
      temp3=0.d0
      sw(i)=swc
      endif
      akrwi=temp3**corey1
      temp4=(1.d0-(sw(i)-swc)/(1.d0-swc))
      if(temp4.lt.0.d0)then
      temp4=0.d0
      sw(i)=1.0d0
      endif
      akrni=corey3*(temp4**corey2)
      flamn(i)=akrni/viscn
      flamw(i)=akrwi/viscw
      flamt(i)=flamn(i)+flamw(i)
      fw(i)=flamw(i)/flamt(i)
      fn(i)=flamn(i)/flamt(i)
      sn(i)=1.d0-sw(i)
    4 continue
c
c     Calculate Capillary Pressure Data
c     Using Log Function
c
      do 88 i=1,ncells
      temp5=(sw(i)-swc)/(1.d0-swc)
      if(temp5.le.0.d0)then
      temp5=.0001
      sw(i)=swc
      endif
      pc(i)=-sig*log(temp5)+pe
      if(pc(i).eq.pe)then
      pc(i)=0.d0
      endif
   88 continue
      pc(ncells)=0.d0
c
c     For coreflooding, injection rate and total velocity remain constant
c
c
c     Increase timestep size if time > 500
c
      if(nstep.eq.1000)dt=1.0
c
c     Increase timestep size if time > 1000
```

```
c
      if(nstep.eq.1500)dt=2.0d0
c      print*,'TOTAL VELOCITY = ',ut
      do 90 j=1,ncells
      snold(j)=sn(j)
      swold(j)=sw(j)
   90 continue
c
c     Solve saturation equations explicitly
c
      sw(1)=sw(1)-(dt/(phi*dx*0.5d0))*(fw(1)*ut+perm*flamn(1)*fw(1)*
     &  (pc(2)-pc(1))/dx)
      do 6 i=2,ncells-1
      sw(i)=sw(i)-(dt/(phi*dx))*((fw(i)-fw(i-1))*ut+perm*flamn(i)*
     &   fw(i)*(pc(i+1)-pc(i))/dx+perm*flamn(i-1)*fw(i-1)*
     &   (pc(i-1)-pc(i))/dx)
    6 continue
c
c     Outlet face cell water saturation always equals 1.0
c
      if(pe.eq.0.d0)go to 16
      sw(ncells)=1.0d0
   16 continue
c
c     Outlet face boundary condition
c     Production is calculated using fractional flow
c     from cell (ncell-1)
c
      uw39=fw(ncells-1)*(ut+perm*flamn(ncells-1)*
     &   (pc(ncells-1)-pc(ncells))/dx)
      qwprod=uw39*area
      qnprod=qinj-qwprod
c
c     Calculate pore volume produced
c
      porvol=porvol+qwprod*dt/(cplength*area*phi)
      rec=porvol
c
c     Material balance check
c
      recmbl=0.d0
      do 80 i=1,ncells-2
      recmbl=recmbl+sw(i+1)
   80 continue
      recmb=(1.d0/dfloat(ncells-1))*(2.d0*recmbl+sw(1)+
     &   sw(ncells))*0.5d0
      recmb=(1.-recmb)
c
c     Print results and go back to next timestep
c
c      write(11,*)time,porvol
c      write(12,*)time,porvol,recmb
c      write(6,100)nstep,time,porvol,qwprod
c 100 format(/,' step ',i7,' Time ',f11.5,' PV ',f6.5,
c    & ' Water ',f10.7)
c
c      Compare times for history match check
c
      if(k.gt.nobs)go to 105
      diftim=timo(k)-time
      if(diftim.le.0.d0)then
      calcrec(k)=recmb
      erc(k)=recmb
      k=k+1
      endif
  105 continue
```

```
c        write(67,1009)k,recmb,rec
        if(time.lt.tend) go to 2
        write(67,104)kkk
  104 format('end of run ',i3)
c
c
c      Least Squares History Matching
c
c
        write(67,40)corey1,corey2,corey3
 40    format(5x,'c1=',f12.6,'c2=',f12.6,5x,'c3=',f12.6)
c       write(67,41)(j,timo(j),obrec(j),erc(j),calcrec(j),
c     &     weght(j),j=1,nobs)
c 41    format(i3,5x,f12.6,5x,f12.6,5x,f12.6,5x,f12.6,5x,f12.6)
        summ=0.d0
        ssumm=0.d0
        do 30 j=1,nobs
   30 ssumm=ssumm+(obrec(j)-calcrec(j))**2
c   30 summ=summ+(obrec(j)-erc(j))**2
        write(67,*)'residual mb calcrec ',summ,ssumm
        if(kkk.eq.1)then
        do 7 j=1,nobs
        write(67,*)'nobs timo(nobs) ',j,timo(j)
        write(67,*)'obrec(nobs) calcrec(nobs)',obrec(j),calcrec(j)
        calcreco(j)=calcrec(j)
 7      ddobrec(j)=obrec(j)-calcreco(j)
        write(67,*)'c1 c2 c3  ',corey1,corey2,corey3
        corey1p=corey1+dcorey
        temp7=corey1
        corey1=corey1p
        kkk=2
        k=1
        go to 999
        endif
        if(kkk.eq.2)then
        do 8 j=1,nobs
        calcrecw(j)=calcrec(j)
8       drecw(j)=(-calcreco(j)+calcrecw(j))/dcorey
        corey2p=corey2+dcorey
        temp8=corey2
        corey2=corey2p
        corey1=temp7
        kkk=3
        k=1
        go to 999
        endif
        if(kkk.eq.3)then
        do 9 j=1,nobs
        calcrecn(j)=calcrec(j)
9       drecn(j)=(-calcreco(j)+calcrecn(j))/dcorey
        corey3p=corey3+dcorey
        temp9=corey3
        corey3=corey3p
        corey2=temp8
        kkk=4
        k=1
        go to 999
        endif
        if(kkk.eq.4)then
        do 10 j=1,nobs
        calcreck(j)=calcrec(j)
10      dreck(j)=(-calcreco(j)+calcreck(j))/dcorey
        corey3=temp9
        endif
        iter=iter+1
        a11=0.0d0
```

```
      a12=0.0d0
      a13=0.0d0
      a22=0.0d0
      a23=0.0d0
      a33=0.0d0
      b1=0.0d0
      b2=0.0d0
      b3=0.0d0
      do 11 j=1,nobs
      a11=a11+(drecw(j)**2)*weght(j)
      a12=a12+(drecw(j)*drecn(j))*weght(j)
      a13=a13+(drecw(j)*dreck(j))*weght(j)
      a22=a22+(drecn(j)**2)*weght(j)
      a23=a23+(drecn(j)*dreck(j))*weght(j)
      a33=a33+(dreck(j)**2)*weght(j)
      b1=b1+(ddobrec(j)*drecw(j))*weght(j)
      b2=b2+(ddobrec(j)*drecn(j))*weght(j)
 11   b3=b3+(ddobrec(j)*dreck(j))*weght(j)
      write(67,888)iter
  888 format(' iteration = ',i5)
c      write(67,1000)a11,a12,a13
c      write(67,1000)a22,a23,a33
c      write(67,1000)b1,b2,b3
c 1000 format(5x,'coefficients=',3e12.5)
      a31=a13
      a32=a23
      a21=a12
c     solution of dc1,dc2,dc3
       aaaa=a11*a22-a12**2
       bbb=a32*a21-a22*a31
       ann=(b3*a21-b2*a31)*aaaa-(b2*a11-b1*a21)*bbb
       dnn=(a33*a21-a23*a31)*aaaa-(a23*a11-a31*a21)*bbb
       dcorey3=ann/dnn
       rmm=(b2*a11-b1*a21)-dc3*(a23*a11-a13*a21)
       dcorey2=rmm/aaaa
       rmmm=b1-a12*dc2-a13*dc3
       dcorey1=rmmm/a11
       factor=.20
       if(iter.gt.2)factor=.5
       corey1=corey1+dcorey1*factor
       corey2=corey2+dcorey2*factor
       corey3=corey3+dcorey3*factor
      write(67,*)'dc1  dc2  dc3',dcorey1,dcorey2,dcorey3
      write(67,*)'new c1 c2 c3  ',corey1,corey2,corey3
      write(67,*)'  '
      if(corey1.lt.0.2d0)corey1=0.2d0
      if(corey2.lt.0.2d0)corey2=0.2d0
      if(corey3.gt.1.0d0)corey3=0.95d0
      if(corey3.lt.0.3d0)corey3=0.3d0
      if(abs(dcorey1)-toll)50,60,60
 50   if(abs(dcorey2)-toll)70,60,60
 70   if(abs(dcorey3)-toll)81,60,60
 60   continue
      k=1
      kkk=1
      if(iter.gt.25)then
      go to 555
      endif
      go to 999
 81   continue
 555  stop
      end
```

## Appendix D.3 - Centrifuge Model

```
      implicit real*8(a-h,o-z)
      dimension x(100),sw(100),sn(100),fw(100),alpha(100),pc(100)
      dimension snold(100),swold(100),txl(100),omegaxl(100)
      dimension fn(100),flamn(100),flamw(100),flamt(100)
c
c     CENTRIFUGE MODEL WITH COREY RELATIVE PERMEABILITY CURVES
c
      open(11,file='timepvcent',access='sequential')
      rewind(11)
      open(12,file='mbcent',access='sequential')
      rewind(12)
      open(14,file='swcent',access='sequential')
      rewind(14)
      open(8,file='omegaxl4000',access='sequential')
      rewind(8)
c
c     Read in constant parameters
c
      print *,'Input POROSITY (fraction), PERMEABILITY (Darcys)'
      read(5,*)phi,perm
      print *,'Input NON-WETTING VISCOSITY (cp), WETTING VISCOSITY (cp)'
      read(5,*)viscn,viscw
      print*,'Input FLUID DENSITY DIFFERENCE BETWEEN TWO PHASES (g/cc)'
      read(5,*)drho
      print *,'Input COREPLUG LENGTH (cm), X-SEC AREA (sq. cm.)'
      read(5,*)cplength,area
      print *,'Input CENTRIFUGE SPEED (rpm), CENTRIFUGE RADIUS (cm)'
      read(5,*)omega,r
      omega=omega*(2.d0*3.14159d0/60.d0)
      print *,'TIMESTEP SIZE (sec), TEND (sec), NUMBER OF MODEL CELLS'
      read(5,*)dt,tend,ncells
      dx=cplength/dfloat(ncells)
      print*,'Input CAP PRESSURE COEFFICIENT, ENTRY PRESSURE (atm)'
      read(5,*)sig,pe
c
c     Initialize arrays
c
c     For centrifuging, the sample is initially 100% saturated
c     with the wetting phase and is displaced by the non-wetting phase
c
      do 1 i=1,ncells
      x(i)=dx/2.d0+dfloat(i-1)*dx
      sw(i)=1.0d0
      sn(i)=0.0d0
      pc(i)=0.0d0
      alpha(i)=1.d0-cplength/(2.d0*r)+x(i)/r
    1 continue
c
c     Input rotor acceleration data for centrifuge
c     Beta is acceleration factor for gravity term
c
      read(8,*)nxl
      do 23 i=1,nxl
      read(8,*)txl(i),omegaxl(i)
      omegaxl(i)=omegaxl(i)*(2.d0*3.14159d0/60.d0)
   23 continue
      m=1
      beta=(omegaxl(1)/omega)**2
      porvol=0.0d0
      pvw=0.d0
      pvnw=0.d0
      time=0.0d0
      nstep=0
c
c     Calculate mobilities (flamn,flamw,flamt) and fractional flow (fw,fn)
c     using the Corey relative permeability relationship
```

```
c            corey1 = exponential factor for wetting phase
c            corey2 = exponential factor for non-wetting phase
c            corey3 = relative permeability factor for non-wetting phase
c            swc = connate water saturation
c            akrwi = wetting phase relative permeability
c            akrni = non-wetting phase relative permeability
c
      print*,'Input constants and coefficients for Corey relative perme
     &ability'
      print*,'  '
      print*,'COREY1 = exponential factor for wetting phase'
      print*,'COREY2 = exponential factor for non-wetting phase'
      print*,'COREY3 = relative permeability factor for non-wetting pha
     &se'
      print*,'Swc = connate water saturation'
      print*,'  '
      print*,'Input COREY1, COREY2, COREY3'
      read(5,*)corey1,corey2,corey3
      print*,'Input connate water saturation, Swc'
      read(5,*)swc
c
c     Calculate mobilities (flamn,flamw,flamt) and fractional flow (fw,fn)
c     using the Corey relative permeability relationship
c
      do 44 i=1,ncells
      temp=((sw(i)-swc)/(1.d0-swc))
      if(temp.le.0.d0)then
      temp=0.d0
      sw(i)=swc
      endif
      akrwi=temp**corey1
      temp1=(1.d0-(sw(i)-swc)/(1.d0-swc))
      if(temp1.le.0.d0)then
      temp1=0.d0
      sw(i)=1.d0
      endif
      akrni=corey3*(temp1**corey2)
      flamn(i)=akrni/viscn
      flamw(i)=akrwi/viscw
      flamt(i)=flamn(i)+flamw(i)
      fw(i)=flamw(i)/flamt(i)
      fn(i)=flamn(i)/flamt(i)
      sn(i)=1.d0-sw(i)
   44 continue
c
c     Calculate Capillary Pressure Data
c     Using Log Function
c
      do 99 i=1,ncells
      temp2=(sw(i)-swc)/(1.d0-swc)
      if(temp2.le.0.d0)then
      temp2=.0001
      sw(i)=swc
      endif
      pc(i)=-sig*log(temp2)+pe
      if(sn(i).lt.0.d0)then
      sn(i)=0.d0
      sw(i)=1.0d0
      pc(i)=0.d0
      endif
   99 continue
      pc(ncells)=0.d0
c
c     Calculate initial velocity
c
      call totalv(uti,sw,omega,pc,fw,fn,flamn,flamw,flamt,ncells,dx,
```

```
     &   perm,cplength,drho,r,beta,time,nstep)
      ut=uti
      print*,'INITIAL VELOCITY = ',ut
c
c     Calculate change in saturation for first cell from injection
c     using source term ut
c
      sw(1)=sw(1)-(dt*ut)/(phi*dx*0.5d0)-(perm*dt)/(phi*dx*0.5d0)*
     &    (flamn(1)*fw(1)*(pc(2)-pc(1))/dx+9.867d-07*flamn(1)*
     &    fw(1)*drho*(omega**2)*beta*r*alpha(1))
c
c     Calculate capillary pressure boundary condition
c     Non-wetting phase penetrates core to length (xe)
c     Sw = 1.0 for x > xe
c
      if(pe.eq.0.d0) go to 17
      s=cplength/r
      anj=1013250.d0*pe/((omega**2)*r*cplength*drho)
      xe=0.5d0-1.d0/s+((1.d0/s-0.5d0)**2+2.d0*(1.d0-anj)/s)**0.5d0
      xpe=cplength*xe
   17 continue
c
c     Begin stepping forward in time
c
    2 time=time+dt
      nstep=nstep+1
c
c     Check time to see if centrifuge has accelerated to full speed
c
      if(time.ge.txl(nxl))then
      beta=1.0d0
      go to 21
      endif
      if(time.le.txl(m))then
      beta=(omegaxl(m)/omega)**2
      endif
      if(time.gt.txl(m))then
      m=m+1
      endif
   21 continue
c
c     Calculate mobilities (flamn,flamw,flamt) and fractional flow (fw,fn)
c     using the Corey relative permeability relationship
c
      do 4 i=1,ncells
      if(sw(i).ge.1.0d0)then
      sw(i)=1.0d0
      sn(i)=0.d0
      endif
      temp3=((sw(i)-swc)/(1.d0-swc))
      if(temp3.lt.0.d0)then
      temp3=0.d0
      sw(i)=swc
      endif
      akrwi=temp3**corey1
      temp4=(1.d0-(sw(i)-swc)/(1.d0-swc))
      if(temp4.lt.0.d0)then
      temp4=0.d0
      sw(i)=1.d0
      endif
      akrni=corey3*(temp4**corey2)
      flamn(i)=akrni/viscn
      flamw(i)=akrwi/viscw
      flamt(i)=flamn(i)+flamw(i)
      fw(i)=flamw(i)/flamt(i)
      fn(i)=flamn(i)/flamt(i)
```

```
      sn(i)=1.d0-sw(i)
    4 continue
c
c     Calculate Capillary Pressure Data
c     Using Log Function
c
      do 88 i=1,ncells
      temp5=(sw(i)-swc)/(1.d0-swc)
      if(temp5.le.0.d0)then
      sw(i)=swc
      temp5=.0001
      endif
      pc(i)=-sig*log(temp5)+pe
      if(sn(i).lt.0.d0)then
      sn(i)=0.d0
      sw(i)=1.0d0
      endif
   88 continue
      pc(ncells)=0.d0
c
c     For centrifuging, total velocity varies with angular velocity (omega)
c
      utold=ut
      call totalv(uti,sw,omega,pc,fw,fn,flamn,flamw,flamt,ncells,dx,
     &   perm,cplength,drho,r,beta,time,nstep)
      ut=uti
c
c     Increase timestep size if time > 100
c
c      if(time.gt.99.d0.and.time.le.100.d0)dt=dt*2.d0
c
c     Increase timestep size if time > 1000
c
c      if(time.gt.998.d0.and.time.le.1000.d0)dt=dt*5.d0
c      print*,'TOTAL VELOCITY = ',ut
c      print*,'BETA = ',beta
      do 9 j=1,ncells
      snold(j)=sn(j)
      swold(j)=sw(j)
    9 continue
c
c     Solve saturation equations explicitly
c
      sw(1)=sw(1)-(dt/(phi*dx*0.5d0))*(fw(1)*ut+perm*flamn(1)*fw(1)*
     &  (pc(2)-pc(1))/dx+9.867d-07*perm*flamn(1)*fw(1)*drho*
     &  (omega**2)*r*alpha(1)*beta)
      do 6 i=2,ncells-1
      sw(i)=sw(i)-(dt/(phi*dx))*((fw(i)-fw(i-1))*ut+perm*flamn(i)*
     &   fw(i)*(pc(i+1)-pc(i))/dx+perm*flamn(i-1)*fw(i-1)*
     &   (pc(i-1)-pc(i))/dx)
      temp6=(9.867d-07*dt*perm*drho*r*beta*
     &   (omega**2))/(phi*dx)*(flamn(i)*fw(i)*alpha(i)-flamn(i-1)
     &   *fw(i-1)*alpha(i-1))
      sw(i)=sw(i)-temp6
      if(sw(i).ge.1.0d0)then
      sw(i)=1.0d0
      sn(i)=0.d0
      endif
      sn(i)=1.0-sw(i)
    6 continue
c
c     Outlet face cell water saturation always equals 1.0
c
      if(pe.eq.0.d0)go to 16
      sw(ncells)=1.0d0
   16 continue
```

```
c
c     Outlet face boundary condition
c     Only the wetting phase is produced
c     Non-wetting phase build up in the coreplug until
c     total velocity decreases to zero
c
      uw39=fw(ncells-1)*(ut+perm*flamn(ncells-1)*
     &   ((pc(ncells-1)-pc(ncells))/dx+
     &   9.869d-07*drho*(omega**2)*r*alpha(ncells-1)*beta))
      qwprod=uw39*area
      qnprod=0.d0
c
c     Calculate pore volume produced
c
      porvol=porvol+qwprod*dt/(cplength*area*phi)
c
c     Material balance check
c
      recs1=0.d0
      do 8 i=1,ncells-2
      recs1=recs1+sw(i+1)
    8 continue
      recs=(1.d0/(ncells-1))*(2.d0*recs1+sw(1)+sw(ncells))*0.5d0
      recs=1.d0-recs
c
c     Print results and go back to next timestep
c
      weght=1.0
      write(11,*)time,porvol
      write(12,*)time,porvol,recs
c       write(6,100)nstep,time,porvol,qwprod
c 100 format(/,' step ',i7,' Time ',f11.5,' PV ',f6.5,
c     & ' Water ',f10.7)
      if(nstep.eq.100)then
      write(14,*)nstep,time,porvol,qwprod,xpe
      do 101 i=1,ncells
      write(14,*)x(i),sw(i),pc(i)
  101 continue
      endif
      if(nstep.eq.1000)then
      write(14,*)nstep,time,porvol,qwprod,xpe
      do 98 i=1,ncells
      write(14,*)x(i),sw(i),pc(i)
   98 continue
      endif
      if(nstep.eq.2000)then
      write(14,*)nstep,time,porvol,qwprod,xpe
      do 102 i=1,ncells
      write(14,*)x(i),sw(i),pc(i)
  102 continue
      endif
      if(nstep.eq.5000)then
      write(14,*)nstep,time,porvol,qwprod,xpe
      do 103 i=1,ncells
      write(14,*)x(i),sw(i),pc(i)
  103 continue
      endif
      if(time.le.tend)go to 2
      write(14,*)nstep,time,porvol,qwprod,xpe
      do 104 i=1,ncells
      write(14,*)x(i),sw(i),pc(i)
  104 continue
      close(10)
      close(11)
      close(14)
      close(12)
```

```
      stop
      end
c
c
c
c
      subroutine totalv(ut,sw,omega,pc,fw,fn,flamn,flamw,flamt,
     &   ncells,dx,perm,cplength,drho,r,beta,time,nstep)
      implicit real*8(a-h,o-z)
      dimension fw(100),fn(100),pc(100),flamn(100),
     &   sw(100),x(100),flamw(100),flamt(100)
c
c     Calculate distance along core
c
      do 2 i=1,ncells
      x(i)=dx/2.d0+dfloat(i-1)*dx
    2 continue
c
c     Calculate Capillary Pressure/Fractional Flow Function (cpr)
c
      cpr=0.d0
      h=cplength/dfloat(ncells-1)
      do 4 j=2,ncells-1
      cpr=h*(fw(j)*(pc(j)-pc(j-1))/dx)+cpr
    4 continue
      cpr=cpr+(h/2.d0)*((fw(1)*(pc(2)-pc(1))/dx)+fw(ncells)*(pc(ncells)
     &   -pc(ncells-1))/dx)
c
c     Calculate Gravity Term
c
      grav=0.d0
      h=cplength/dfloat(ncells-1)
      do 6 j=2,ncells-1
      grav=grav+h*fw(j)*(1.d0-cplength/(2.d0*r)+x(j)/r)
    6 continue
      grav=grav+(h/2.d0)*((fw(1)*(1.d0-cplength/(2.d0*r)+x(1)/r))+
     &    (fw(ncells)*(1.d0-cplength/(2.d0*r)+x(ncells)/r)))
c
c     Calculate transmissibility term
c
      h=cplength/dfloat(ncells-1)
      alamx=0.d0
      do 8 j=2,ncells-1
      alamx=alamx+h*(1.d0/(perm*flamt(j)))
    8 continue
      alamx=alamx+(h/2.d0)*(1.d0/(perm*flamt(1))+1.d0/(perm
     &   *flamt(ncells)))
c
c     Calculate Total Velocity (ut)
c
      ut=(cpr+9.869d-07*(omega**2)*r*beta*drho*grav)/alamx
      return
      end
```

## Appendix D.4 - Centrifuge Model with Least Squares History Matching

```
      implicit real*8(a-h,o-z)
      dimension x(100),sw(100),sn(100),fw(100),alpha(100),pc(100)
      dimension snold(100),swold(100)
      dimension fn(100),flamn(100),flamw(100),flamt(100)
      dimension timo(1000),obrec(1000),erc(1000),calcrec(1000),
     &  calcreco(1000),ddobrec(1000),drecw(1000),drecn(1000),
     & dreck(1000),calcrecw(1000),
     & calcrecn(1000),calcreck(1000),
     & weght(1000),txl(100),omegaxl(100)
c
c     CENTRIFUGE MODEL WITH COREY RELATIVE PERMEABILITY CURVES
c     HISTORY MATCHING ALGORITM USING LEAST SQUARES
c
      open(7,file='hmdataba2a',access='sequential')
      rewind(7)
      open(11,file='timepv',access='sequential')
      rewind(11)
      open(12,file='mbcent',access='sequential')
      rewind(12)
      open(67,file='itercentba2a',access='sequential')
      rewind(67)
      open(14,file='swcent',access='sequential')
      rewind(14)
      open(8,file='omegaxl4000',access='sequential')
      rewind(8)
c
c     Read in constant parameters
c
      print *,'Input POROSITY (fraction), PERMEABILITY (Darcys)'
      read(5,*)phi,perm
      print *,'Input NON-WETTING VISCOSITY (cp), WETTING VISCOSITY (cp)'
      read(5,*)viscn,viscw
      print*,'Input FLUID DENSITY DIFFERENCE BETWEEN TWO PHASES (g/cc)'
      read(5,*)drho
      print *,'Input COREPLUG LENGTH (cm), X-SEC AREA (sq. cm.)'
      read(5,*)cplength,area
      print *,'Input CENTRIFUGE SPEED (rpm), CENTRIFUGE RADIUS (cm)'
      read(5,*)omega,r
      omega=omega*(2.d0*3.14159d0/60.d0)
      print *,'TIMESTEP SIZE (sec), TEND (sec), NUMBER OF MODEL CELLS'
      read(5,*)dt,tend,ncells
      dtinit=dt
      dx=cplength/dfloat(ncells)
      print*,'Input CAP PRESSURE COEFFICIENT, ENTRY PRESSURE (atm)'
      read(5,*)sig,pe
c
c     Calculate mobilities (flamn,flamw,flamt) and fractional flow (fw,fn)
c     using the Corey relative permeability relationship
c             corey1 = exponential factor for wetting phase
c             corey2 = exponential factor for non-wetting phase
c             corey3 = relative permeability factor for non-wetting phase
c             swc = connate water saturation
c             akrwi = wetting phase relative permeability
c             akrni = non-wetting phase relative permeability
c
      print*,'Input constants and coefficients for Corey relative permea
     &bility'
      print*,'  '
      print*,'COREY1 = exponential factor for wetting phase'
      print*,'COREY2 = exponential factor for non-wetting phase'
      print*,'COREY3 = relative permeability factor for non-wetting phas
     &e'
      print*,'Swc = connate water saturation'
      print*,'  '
      print*,'Input COREY1, COREY2, COREY3'
      read(5,*)corey1,corey2,corey3
```

```
      print*,'Input connate water saturation, Swc'
      read(5,*)swc
c
c     Read history match recovery data
c
      read(7,*)nobs,dcorey,toll
      read(7,*)(j,timo(j),obrec(j),weght(j),j=1,nobs)
c
c     Initialize arrays
c
c     For centrifuging, the sample is initially 100% saturated
c     with the wetting phase and is displaced by the non-wetting phase
c
      k=1
      kkk=1
      iter=0
c
c     Input rotor acceleration data for centrifuge
c     Beta is acceleration factor for gravity term
c
      read(8,*)nxl
      do 23 i=1,nxl
      read(8,*)txl(i),omegaxl(i)
      omegaxl(i)=omegaxl(i)*(2.d0*3.14159d0/60.d0)
   23 continue
  999 continue
      do 1 i=1,ncells
      x(i)=dx/2.d0+dfloat(i-1)*dx
      sw(i)=1.0d0
      sn(i)=0.0d0
      pc(i)=0.0d0
      alpha(i)=1.d0-cplength/(2.d0*r)+x(i)/r
    1 continue
      k=1
      m=1
      beta=(omegaxl(1)/omega)**2
      porvol=0.0d0
      pvw=0.d0
      pvnw=0.d0
      time=0.0d0
      nstep=0
      dt=dtinit
c
c     Calculate mobilities (flamn,flamw,flamt) and fractional flow (fw,fn)
c     using the Corey relative permeability relationship
c
      do 44 i=1,ncells
      temp=((sw(i)-swc)/(1.d0-swc))
      if(temp.lt.0.d0)then
      temp=0.d0
      sw(i)=swc
      endif
      akrwi=temp**corey1
      temp1=(1.d0-(sw(i)-swc)/(1.d0-swc))
      if(temp1.lt.0.d0)then
      temp1=0.d0
      sw(i)=1.0d0
      endif
      akrni=corey3*(temp1**corey2)
      flamn(i)=akrni/viscn
      flamw(i)=akrwi/viscw
      flamt(i)=flamn(i)+flamw(i)
      fw(i)=flamw(i)/flamt(i)
      fn(i)=flamn(i)/flamt(i)
      sn(i)=1.d0-sw(i)
   44 continue
```

```
c
c     Calculate Capillary Pressure Data
c     Using Log Function
c
      do 99 i=1,ncells
      temp2=(sw(i)-swc)/(1.d0-swc)
      if(temp2.le.0.d0)then
      temp2=.0001
      sw(i)=swc
      endif
      pc(i)=-sig*log(temp2)+pe
   99 continue
      pc(ncells)=0.d0
c
c     Calculate initial velocity
c
      call totalv(uti,sw,omega,pc,fw,fn,flamn,flamw,flamt,ncells,dx,
     &   perm,cplength,drho,r,beta)
      ut=uti
c      print*,'INITIAL VELOCITY = ',ut
c
c     Calculate change in saturation for first cell from injection
c     using source term ut
c
      sw(1)=sw(1)-(dt*ut)/(phi*dx*0.5d0)-(perm*dt)/(phi*dx*0.5d0)*
     &   (flamn(1)*fw(1)*(pc(2)-pc(1))/dx+9.867d-07*flamn(1)*
     &   fw(1)*drho*(omega**2)*r*beta*alpha(1))
c
c     Calculate capillary pressure boundary condition
c     Non-wetting phase penetrates core to length (xe)
c     Sw = 1.0 for x > xe
c
      if(pe.eq.0.d0) go to 17
      s=cplength/r
      anj=1013250.d0*pe/((omega**2)*r*cplength*drho)
      xe=0.5d0-1.d0/s+((1.d0/s-0.5d0)**2+2.d0*(1.d0-anj)/s)**0.5d0
      xpe=cplength*xe
   17 continue
c
c     Begin stepping forward in time
c
    2 continue
      time=time+dt
      nstep=nstep+1
c
c     Check time to see if centrifuge has accelerated to full speed
c
      if(time.ge.txl(nxl))then
      beta=1.0d0
      go to 21
      endif
      if(time.le.txl(m))then
      beta=(omegaxl(m)/omega)**2
      endif
      if(time.gt.txl(m))then
      m=m+1
      endif
   21 continue
c
c     Calculate mobilities (flamn,flamw,flamt) and fractional flow (fw,fn)
c     using the Corey relative permeability relationship
c
      do 4 i=1,ncells
      if(sw(i).ge.1.0d0)then
      sw(i)=1.0d0
      sn(i)=0.d0
```

```
      endif
      temp3=((sw(i)-swc)/(1.d0-swc))
      if(temp3.lt.0.d0)then
      temp3=0.d0
      sw(i)=swc
      endif
      akrwi=temp3**corey1
      temp4=(1.d0-(sw(i)-swc)/(1.d0-swc))
      if(temp4.lt.0.d0)then
      temp4=0.d0
      sw(i)=1.0d0
      endif
      akrni=corey3*(temp4**corey2)
      flamn(i)=akrni/viscn
      flamw(i)=akrwi/viscw
      flamt(i)=flamn(i)+flamw(i)
      fw(i)=flamw(i)/flamt(i)
      fn(i)=flamn(i)/flamt(i)
      sn(i)=1.d0-sw(i)
    4 continue
c
c     Calculate Capillary Pressure Data
c     Using Log Function
c
      do 88 i=1,ncells
      temp5=(sw(i)-swc)/(1.d0-swc)
      if(temp5.le.0.d0)then
      temp5=.0001
      sw(i)=swc
      endif
      pc(i)=-sig*log(temp5)+pe
   88 continue
      pc(ncells)=0.d0
c
c     For centrifuging, total velocity varies with angular velocity (omega)
c
      utold=ut
      call totalv(uti,sw,omega,pc,fw,fn,flamn,flamw,flamt,ncells,dx,
     &   perm,cplength,drho,r,beta)
      ut=uti
c
c     Increase timestep size if time > 100 seconds
c
      if(nstep.eq.1000)dt=0.2d0
c
c     Increase timestep size if time > 500
c
      if(nstep.eq.3000)dt=0.5d0
c
c     Increase timestep size if time > 1000
c
      if(nstep.eq.4000.)dt=1.0d0
c      print*,'TOTAL VELOCITY = ',ut
      do 90 j=1,ncells
      snold(j)=sn(j)
      swold(j)=sw(j)
   90 continue
c
c     Solve saturation equations explicitly
c
      sw(1)=sw(1)-(dt/(phi*dx*0.5d0))*(fw(1)*ut+perm*flamn(1)*fw(1)*
     &  (pc(2)-pc(1))/dx+9.867d-07*perm*flamn(1)*fw(1)*drho*
     &  (omega**2)*r*alpha(1)*beta)
      do 6 i=2,ncells-1
      sw(i)=sw(i)-(dt/(phi*dx))*((fw(i)-fw(i-1))*ut+perm*flamn(i)*
     &   fw(i)*(pc(i+1)-pc(i))/dx+perm*flamn(i-1)*fw(i-1)*
```

```
      &   (pc(i-1)-pc(i))/dx)
       temp6=(9.867d-07*dt*perm*drho*r*beta*
      &   (omega**2))/(phi*dx)*(flamn(i)*fw(i)*alpha(i)-flamn(i-1)
      &   *fw(i-1)*alpha(i-1))
       sw(i)=sw(i)-temp6
       if(sw(i).ge.1.0d0)then
       sw(i)=1.0d0
       sn(i)=0.d0
       endif
     6 continue
c
c      Outlet face cell water saturation always equals 1.0
c
       if(pe.eq.0.d0)go to 16
       sw(ncells)=1.0d0
    16 continue
c
c      Outlet face boundary condition
c      Only the wetting phase is produced
c      Non-wetting phase build up in the coreplug until
c      total velocity decreases to zero
c
       uw39=fw(ncells-1)*(ut+perm*flamn(ncells-1)*
      &   ((pc(ncells-1)-pc(ncells))/dx+
      &   9.869d-07*drho*(omega**2)*r*alpha(ncells-1)*beta))
       qwprod=uw39*area
       qnprod=0.d0
c
c      Calculate pore volume produced
c
       porvol=porvol+qwprod*dt/(cplength*area*phi)
       rec=porvol
c
c      Material balance check
c
       recmbl=0.d0
       do 80 i=1,ncells-2
       recmbl=recmbl+sw(i+1)
    80 continue
       recmb=(1.d0/dfloat(ncells-1))*(2.d0*recmbl+sw(1)+
      &   sw(ncells))*0.5d0
       recmb=(1.d0-recmb)
c
c      Print results and go back to next timestep
c
c       write(11,*)time,porvol
c       write(12,*)time,porvol,recmb
c       write(6,100)nstep,time,porvol,qwprod
c   100 format(/,' step ',i7,' Time ',f11.5,' PV ',f6.5,
c      & ' Water ',f10.7)
c
c       Compare times for history match check
c
       if(k.gt.nobs)then
       go to 105
       endif
       diftim=timo(k)-time
       if(diftim.le.0.d0)then
       calcrec(k)=recmb
       erc(k)=recmb
c       write(67,*)'k  time  timo(k)  ',k,time,timo(k)
c       write(67,*)'obrec(k)  calcrec',obrec(k),rec
       k=k+1
       endif
   105 continue
       if(time.lt.tend) go to 2
```

```
      write(67,104)kkk
  104 format('end of run ',i3)
c
c
c     Least Squares History Matching
c
c
      write(67,*)'c1= ',corey1,'c2= ',corey2,'c3= ',corey3
c       write(67,41)(j,timo(j),obrec(j),erc(j),calcrec(j),
c    &     weght(j),j=1,nobs)
c 41    format(i3,5x,f12.6,5x,f12.6,5x,f12.6,5x,f12.6,5x,f12.6)
      summ=0.d0
      ssumm=0.d0
      do 30 j=1,nobs
   30 ssumm=ssumm+(obrec(j)-calcrec(j))**2
c   30 summ=summ+(obrec(j)-erc(j))**2
      write(67,*)'residual calcrec ',ssumm
      if(kkk.eq.1)then
      do 7 j=1,nobs
      calcreco(j)=calcrec(j)
      write(67,*)'nobs  timo(nobs)   ',j,timo(j)
      write(67,*)'obrec(nobs)   calcrec(nobs)   ',obrec(j),calcrec(j)
 7    ddobrec(j)=obrec(j)-calcreco(j)
      corey1p=corey1+dcorey
      temp7=corey1
      corey1=corey1p
      kkk=2
      k=1
      go to 999
      endif
      if(kkk.eq.2)then
      do 8 j=1,nobs
      calcrecw(j)=calcrec(j)
8     drecw(j)=(-calcreco(j)+calcrecw(j))/dcorey
      corey2p=corey2+dcorey
      temp8=corey2
      corey2=corey2p
      corey1=temp7
      kkk=3
      k=1
      go to 999
      endif
      if(kkk.eq.3)then
      do 9 j=1,nobs
      calcrecn(j)=calcrec(j)
9     drecn(j)=(-calcreco(j)+calcrecn(j))/dcorey
      corey3p=corey3+dcorey
      temp9=corey3
      corey3=corey3p
      corey2=temp8
      kkk=4
      k=1
      go to 999
      endif
      if(kkk.eq.4)then
      do 10 j=1,nobs
      calcreck(j)=calcrec(j)
10    dreck(j)=(-calcreco(j)+calcreck(j))/dcorey
      corey3=temp9
      endif
      iter=iter+1
      a11=0.0d0
      a12=0.0d0
      a13=0.0d0
      a22=0.0d0
      a23=0.0d0
```

```
      a33=0.0d0
      b1=0.0d0
      b2=0.0d0
      b3=0.0d0
      do 11 j=1,nobs
      a11=a11+(drecw(j)**2)*weght(j)
      a12=a12+(drecw(j)*drecn(j))*weght(j)
      a13=a13+(drecw(j)*dreck(j))*weght(j)
      a22=a22+(drecn(j)**2)*weght(j)
      a23=a23+(drecn(j)*dreck(j))*weght(j)
      a33=a33+(dreck(j)**2)*weght(j)
      b1=b1+(ddobrec(j)*drecw(j))*weght(j)
      b2=b2+(ddobrec(j)*drecn(j))*weght(j)
 11   b3=b3+(ddobrec(j)*dreck(j))*weght(j)
      write(67,888)iter
  888 format(' iteration = ',i5)
c      write(67,1000)a11,a12,a13
c      write(67,1000)a22,a23,a33
c      write(67,1000)b1,b2,b3
c 1000 format(5x,'coefficients=',3e12.5)
      a31=a13
      a32=a23
      a21=a12
c
c     Solution of dc1,dc2,dc3 using Cramer's Rule
c
       aaaa=a11*a22-a12**2
       bbb=a32*a21-a22*a31
       ann=(b3*a21-b2*a31)*aaaa-(b2*a11-b1*a21)*bbb
       dnn=(a33*a21-a23*a31)*aaaa-(a23*a11-a31*a21)*bbb
       dcorey3=ann/dnn
       rmm=(b2*a11-b1*a21)-dc3*(a23*a11-a13*a21)
       dcorey2=rmm/aaaa
       rmmm=b1-a12*dc2-a13*dc3
       dcorey1=rmmm/a11
       factor=.20
       if(iter.gt.2)factor=.5
       corey1=corey1+dcorey1*factor
       corey2=corey2+dcorey2*factor
       corey3=corey3+dcorey3*factor
      write(67,*)'dc1  dc2  dc3  ',dcorey1,dcorey2,dcorey3
      write(67,*)'new c1 c2 c3',corey1,corey2,corey3
      write(67,*)'   '
      if(corey1.lt.0.2d0)corey1=0.5d0
      if(corey2.lt.0.2d0)corey2=0.5d0
      if(corey3.gt.1.0d0)corey3=0.95d0
      if(corey3.lt.0.d0)corey3=0.3d0
      if(abs(dcorey1)-toll)50,60,60
 50   if(abs(dcorey2)-toll)70,60,60
 70   if(abs(dcorey3)-toll)81,60,60
 60   continue
      k=1
      kkk=1
      if(iter.gt.1)then
      go to 555
      endif
      go to 999
 81   continue
 555  stop
      end
c
c
c
      subroutine totalv(ut,sw,omega,pc,fw,fn,flamn,flamw,flamt,
     &   ncells,dx,perm,cplength,drho,r,beta)
      implicit real*8(a-h,o-z)
```

```
      dimension fw(100),fn(100),pc(100),flamn(100),
     &   sw(100),x(100),flamw(100),flamt(100)
c
c     Calculate distance along core
c
      do 2 i=1,ncells
      x(i)=dx/2.d0+dfloat(i-1)*dx
    2 continue
c
c     Calculate Capillary Pressure/Fractional Flow Function (cpr)
c
      cpr=0.d0
      h=cplength/dfloat(ncells-1)
      do 4 j=2,ncells-1
      cpr=h*(fw(j)*(pc(j)-pc(j-1))/dx)+cpr
    4 continue
      cpr=cpr+(h/2.d0)*((fw(1)*(pc(2)-pc(1))/dx)+fw(ncells)*(pc(ncells)
     &   -pc(ncells-1))/dx)
c
c     Calculate Gravity Term
c
      grav=0.d0
      h=cplength/dfloat(ncells-1)
      do 6 j=2,ncells-1
      grav=grav+h*fw(j)*(1.d0-cplength/(2.d0*r)+x(j)/r)
    6 continue
      grav=grav+(h/2.d0)*((fw(1)*(1.d0-cplength/(2.d0*r)+x(1)/r))+
     &    (fw(ncells)*(1.d0-cplength/(2.d0*r)+x(ncells)/r)))
c
c     Calculate transmissibility term
c
      h=cplength/dfloat(ncells-1)
      alamx=0.d0
      do 8 j=2,ncells-1
      alamx=alamx+h*(1.d0/(perm*flamt(j)))
    8 continue
      alamx=alamx+(h/2.d0)*(1.d0/(perm*flamt(1))+1.d0/(perm
     &    *flamt(ncells)))
c
c     Calculate Total Velocity (ut)
c
      ut=(cpr+9.869d-07*(omega**2)*r*beta*drho*grav)/alamx
      return
      end
```

# Appendix E - Experimental Data

Chevron

**Chevron Oil Field Research Company**
A Chevron Corporation Subsidiary
1300 Beach Boulevard, La Habra, California
Mail Address PO Box 446, La Habra, CA 90633 0446

May 3, 1988

LH-1705-1
COOPERATIVE RESEARCH PROJECT

Dr. Khalid Aziz
Dept. of Petroleum Engineering
Stanford University
Stanford, CA 94305-2170

Attn: David Shimbo

Dear Dr. Aziz:

Attached for your information are sets of coreflood and centrifuge production data from experiments on Berea sandstone samples. The data may be useful for comparing relative permeabilities derived from both types of experiments. Similar data on two other types of sandstone may be available in the near future.

The transmittal of the attached data is related to cooperative research project LH-1705-1 as outlined in previous correspondence (J. E. Briggs-K. Aziz, 12/2/87 and 12/14/87). We look forward to hearing from you in the near future. If there are any further questions regarding the attached data, please contact Mr. E. F. deZabala at (213) 694-9102.

Very truly yours,

E. F. deZabala

F. G. McCaffery

Attach: Description of Displacement Data and Experimental Protocol

## DESCRIPTION OF DISPLACEMENT DATA AND EXPERIMENTAL PROTOCOL

The following datasets describe the results of displacement tests performed using Berea sandstone plugs. Two types of displacement tests are described: corefloods and centrifuge displacements. All tests were performed in the drainage mode, with gas (nitrogen or air) displacing depolarized white oil or with depolarized kerosene displacing a glycerol/brine mixture. The displacement results are split into two major sections: I) gas/oil drainage experiments using Berea core BA-1, and II) glycerol-brine/oil drainage experiments using Berea core BA-2.

For the sake of experimental consistency and convenience, all of the cores (BA-1) used in the gas/oil drainage experiments were saturated 100% with oil. No attempts were made to establish a connate water saturation: a protocol that allows for experimental consistency (also convenience) and comparison of data from the two types of displacements.

## EXPERIMENTAL PROTOCOL

For each Berea core the following protocol was followed:

1) Measure air permeability and helium porosity for the long core (ca., 4.5" long and 1" diameter).

2) Saturate core with wetting phase and perform an unsteady-state drainage relative permeability test.

3) Extract core with sequences of toluene and methanol and then dry the core.

4) Section the core into four (4) approximately equal segments (ca., 1"-long). Measure the air permeability and helium porosity on each segment. The four segments of each core are denoted by the letters A, B, C, and D (e.g., BA-1C), with A denoting the injection end and D denoting the outlet end of the core as it was used in Step 2.

5) Resaturate the core segments with the wetting phase and measure the drainage capillary pressure in a centrifuge (Beckman L8-55M/P ultracentrifuge).

6) Clean and dry the cores for air permeability measurements.

7) Using permeability and capillary pressure curves as selection criteria, two (2) of the most representative plugs are selected for further centrifuge measurements.

8) Resaturate the cores and measure transient wetting phase production in the centrifuge at several rotational speeds (e.g., 1000, 2000, and 3000 rpm). After each measurement, the cores are cleaned, dried, and resaturated for the next experiment.

EXPERIMENTAL DATA

The attached tables and figures contain all of the data that are necessary to model the experiments. The data are organized according to the following outline:

---

I) Gas/Oil Drainage Experiments Using Berea Core BA-1

A) Unsteady-State Drainage Relative Permeability Test.

1) Table of Core & Fluid Properties

2) Table of Gas/Oil Production Data

3) Figure - Oil Production vs. Pore Volumes

4) Figure - Time vs. Pore Volumes Injected (pore volumes calculated at the average gas pressure 17.7 psi)

B) Drainage Capillary Pressure Tests Using Four Core Segments.

1) Figure - Capillary Pressure Data for plugs BA-1A, B, C, and D.

2) Table of Air Permeability Data

3) Capillary Pressure and J-function Data for plugs BA-1A, B, C, and D.

C) Measurement of Rotor Acceleration Function for Beckman L8-55M/P Ultracentrifuge (* See Below).

1) Table of Transient Rotor Speed Data for for Acceleration from 0 rpm to 1000, 2000, 3000, or 4000 rpm.

2) Figure - Rotor Speed vs. Time.

D) Transient Oil Production in the Centrifuge During Drainage by Air (Tables and Figures).

1) Core BA-1A Tests.

a) 1000 rpm (Figure and Table)
b) 2000 rpm (Figure and Table)
c) 3000 rpm (Figure and Table)

2) Core BA-1D Tests.

a) 1000 rpm (Figure and Table)
b) 2000 rpm (Figure and Table)
c) 3000 rpm (Figure and Table]

---

II) Glycerol-Brine/Oil Drainage Experiments Using Berea Core BA-2.

A) Unsteady-State Drainage Relative Permeability Test (constant flow rate).

1) Table of Core & Fluid Properties.

2) Table of Glycerol-Brine/Oil Production Data.

3) Figure - Volume of Produced Glycerol-Brine vs. Pore Volumes Injected.

4) Figure - Pressure Drop vs. Pore Volumes Injected.

B) Drainage Capillary Pressure Tests Using Four Core Segments.

1) Figure - Capillary Pressure Data for Berea Cores BA-2A, B, C, and D.

2) Tables of Capillary Pressure and J-function Data.

a) Plug BA-2A
b) Plug BA-2B
c) Plug BA-2C
d) Plug BA-2D

C) Transient Production in the Centrifuge During Drainage by Kerosene.

1) Core BA-2A Test.

a) 4000 rpm (Figure and Table)

2) Core BA-2C Test.

a) 3000 rpm (Figure and Table)

---

* - Our preliminary results have indicated that the initial acceleration of the centrifuge rotor (from 0 to the preset rpm) has a profound effect on transient production data, especially at early times. The rotor acceleration data may be useful for matching the early-time wetting-phase production data (i.e., when rapid production occurs).

# SECTION I

TABLE IA-1. CORE AND FLUID PROPERTIES FOR GAS/OIL DRAINAGE OF BEREA CORE BA-1

| | | |
|---|---|---|
| FIELD NAME (OPTIONAL) | : | BEREA PLUG |
| WELL NUMBER (OPTIONAL) | : | |
| CORE DEPTH (OPTIONAL) | : | Feet |
| CORE I.D. (OPTIONAL) | : | BA-1 |
| OIL VISCOSITY | = | 15 cp |
| GAS VISCOSITY | = | .0177 cp |
| OIL DENSITY | = | .8355 g/cc |
| GAS DENSITY | = | .0012 g/cc |
| DPT FLUID DENSITY | = | 0 g/cc |
| INITIAL WATER SATURATION | = | 0 % |
| BASE PERMEABILITY | = | 517 md |
| PORE VOLUME | = | 12.491 cc |
| CORE LENGTH | = | 11.495 cm |
| CORE DIAMETER | = | 2.526 cm |
| POROSITY (OPTIONAL) | = | 21.7 % |
| AIR PERM (OPTIONAL) | = | 517 md |
| PRESSURE DROP | = | 6 psi |
| DEAD VOLUME | = | 0 cc |
| DOWNSTREAM DEAD VOLUME | = | 0 cc |
| LEAK RATE | = | 0 cc/min |
| AXIS ORIENTATION | = | 0 degrees |
| TEST TEMPERATURE (OPTIONAL) | = | 74 degrees F |
| AVERAGE OVERBURDEN PRESSURE (OPTIONAL) | = | 400 psi |

TABLE IA-2. GAS/OIL DRAINAGE PRODUCTION DATA FOR BEREA CORE BA-1

| Point Number | Time (min) | Oil Prod. (cc) | Gas Prod. (cc, 14.7 psi) | Gas Prod. (cc, 17.7 psi) |
|---|---|---|---|---|
| 1 | .80 | .06 | 0. | 0. |
| 2 | .93 | .11 | 1. | .83 |
| 3 | 1.39 | .34 | 2. | 1.66 |
| 4 | 2.21 | .80 | 4. | 3.32 |
| 5 | 2.70 | 1.03 | 6. | 4.98 |
| 6 | 3.06 | 1.17 | 8. | 6.64 |
| 7 | 3.39 | 1.29 | 10. | 8.31 |
| 8 | 4.51 | 1.64 | 20. | 16.61 |
| 9 | 5.32 | 1.87 | 30. | 24.92 |
| 10 | 6.00 | 2.02 | 40. | 33.22 |
| 11 | 6.60 | 2.17 | 48. | 39.86 |
| 12 | 7.12 | 2.26 | 60. | 49.83 |
| 13 | 7.69 | 2.37 | 70. | 58.14 |
| 14 | 8.08 | 2.48 | 80. | 66.44 |
| 15 | 8.48 | 2.53 | 90. | 74.75 |
| 16 | 8.91 | 2.62 | 100. | 83.05 |
| 17 | 9.84 | 2.76 | 125. | 103.81 |
| 18 | 10.81 | 2.92 | 150. | 124.58 |
| 19 | 12.05 | 3.11 | 200. | 166.10 |
| 20 | 13.37 | 3.28 | 250. | 207.63 |
| 21 | 14.55 | 3.44 | 300. | 249.15 |
| 22 | 16.70 | 3.64 | 400. | 332.20 |
| 23 | 18.64 | 3.82 | 500. | 415.25 |
| 24 | 20.33 | 3.96 | 600. | 498.30 |
| 25 | 21.95 | 4.12 | 700. | 581.35 |
| 26 | 23.55 | 4.24 | 800. | 664.40 |
| 27 | 24.99 | 4.32 | 900. | 747.45 |
| 28 | 26.38 | 4.40 | 1000. | 830.50 |
| 29 | 29.80 | 4.64 | 1250. | 1038.13 |
| 30 | 33.19 | 4.81 | 1500. | 1245.75 |
| 31 | 38.93 | 5.07 | 2000. | 1661.00 |
| 32 | 44.18 | 5.24 | 2500. | 2076.25 |
| 33 | 49.11 | 5.37 | 3000. | 2491.50 |
| 34 | 53.70 | 5.51 | 3500. | 2906.75 |
| 35 | 58.42 | 5.65 | 4000. | 3322.00 |
| 36 | 62.85 | 5.72 | 4500. | 3737.25 |
| 37 | 67.65 | 5.79 | 5000. | 4152.50 |
| 38 | 71.49 | 5.89 | 5500. | 4567.75 |
| 39 | 75.80 | 5.95 | 6000. | 4983.00 |
| 40 | 79.38 | 6.00 | 6500. | 5398.25 |

Inlet Pressure = 20.7 psi
Outlet Pressure = 14.7 psi
Average Pressure = 17.7 psi

Figure IA-1

OIL PRODUCTION -- BA-1 GAS DRIVE

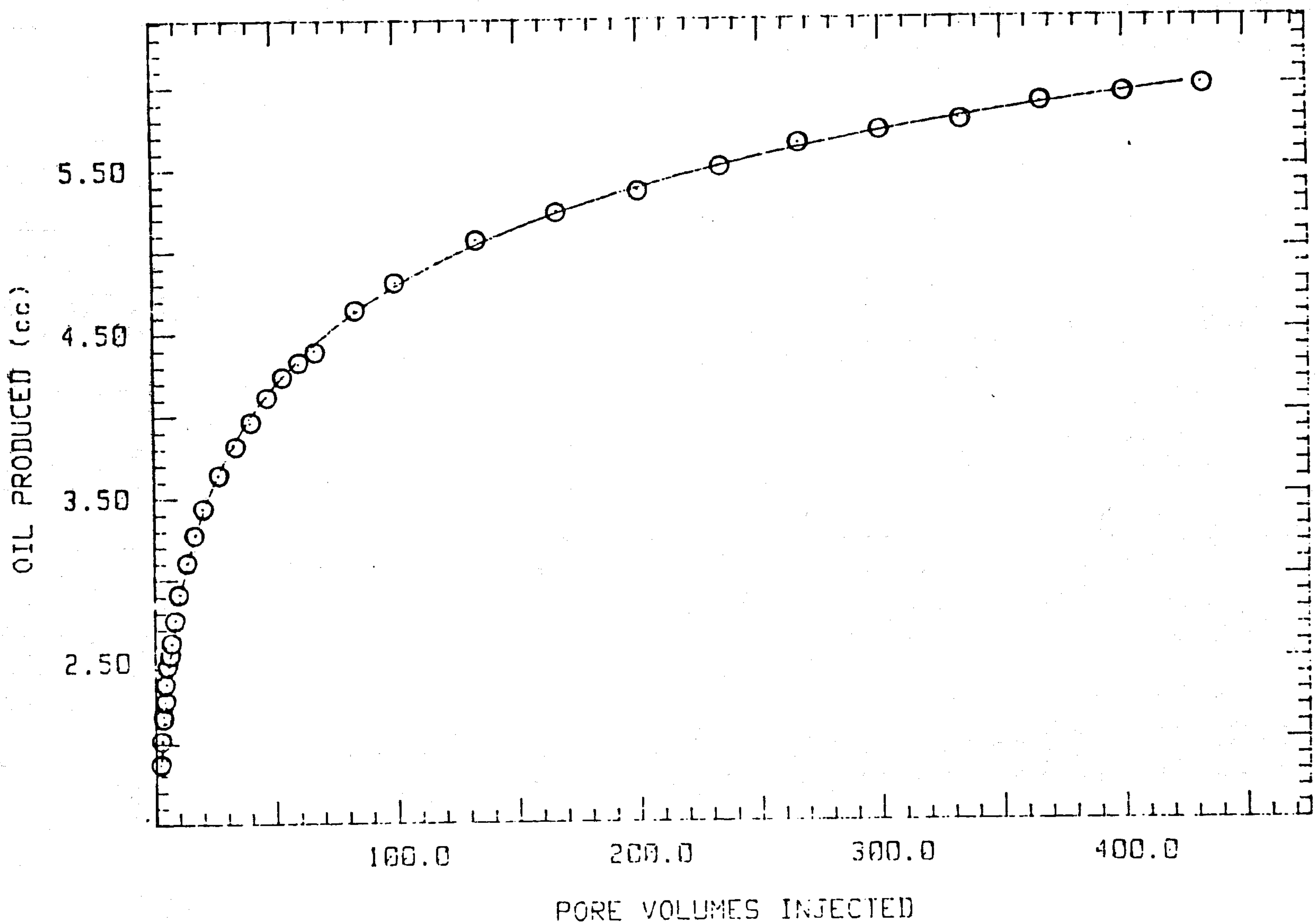


Figure IA-2

TOTAL PRODUCTION - BA-1 GAS DRIVE

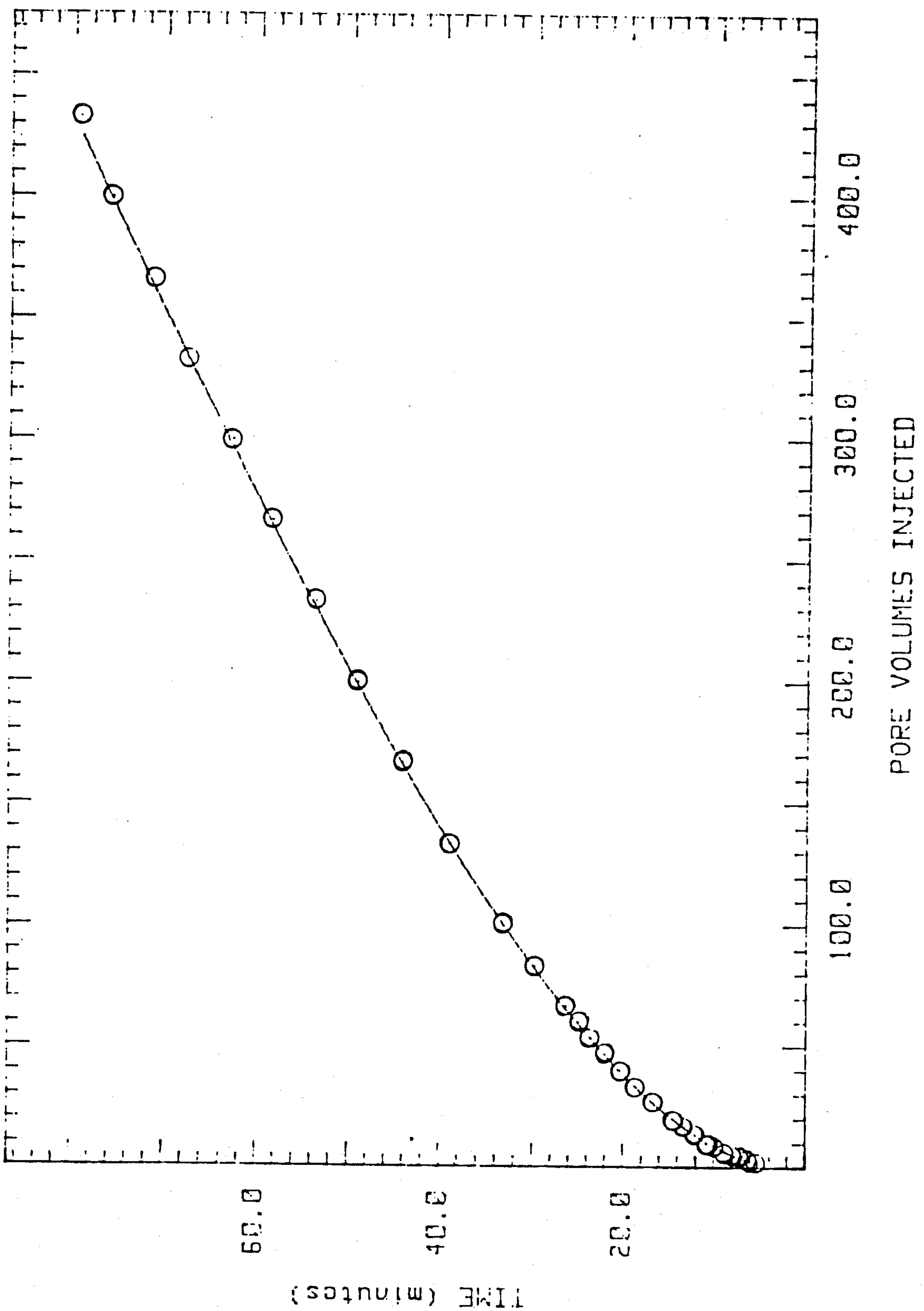


Figure IB-1

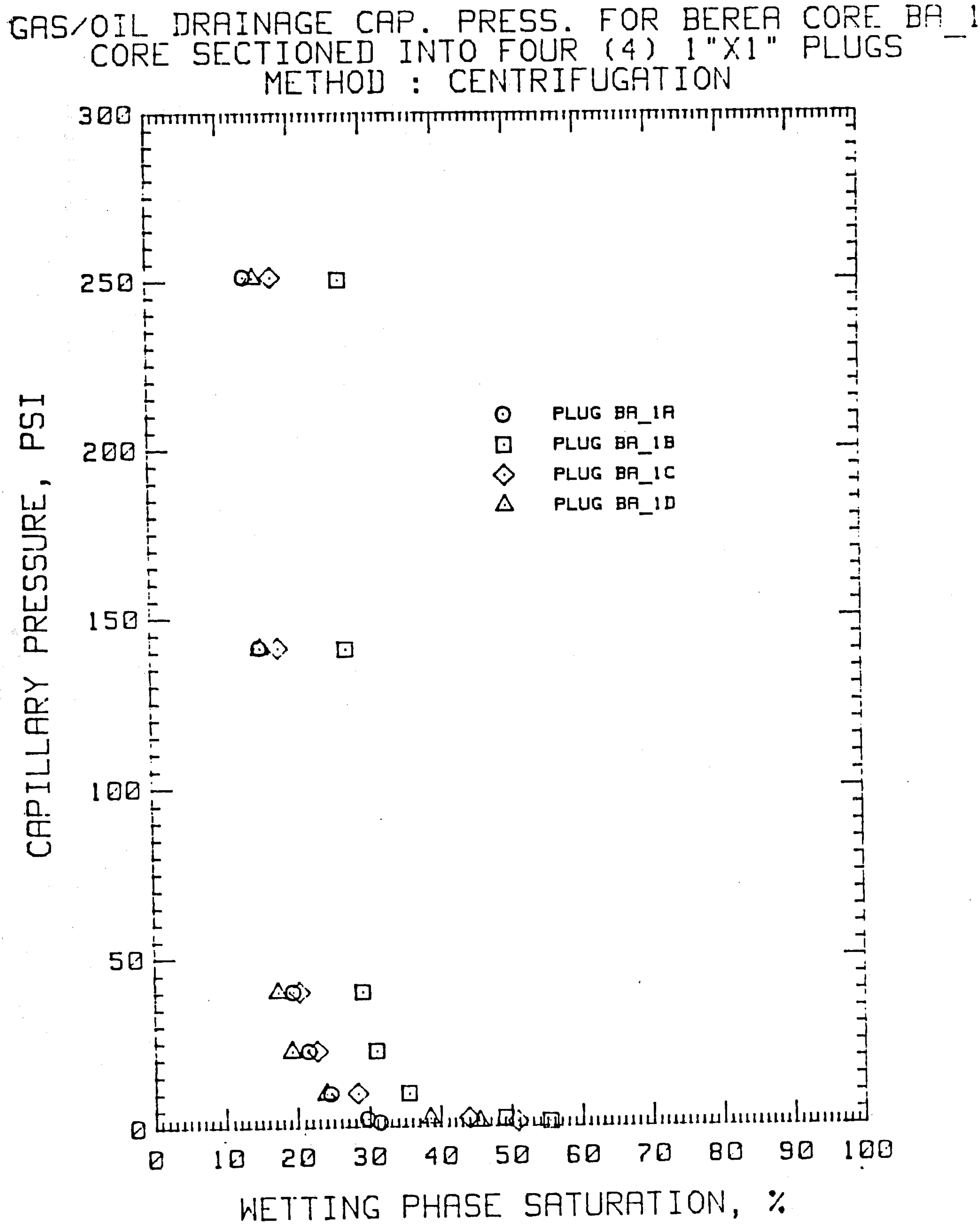

GAS/OIL DRAINAGE CAP. PRESS. FOR BEREA CORE BA_1
CORE SECTIONED INTO FOUR (4) 1"X1" PLUGS
METHOD : CENTRIFUGATION
CAPILLARY PRESSURE, PSI
300
250
200
150
100
50
0
0
10
20
30
40
50
60
70
80
90
100
WETTING PHASE SATURATION, %
PLUG BA_1A
PLUG BA_1B
PLUG BA_1C
PLUG BA_1D

TABLE IB-1. AIR PERMEABILITY OF 1" x 1" BEREA PLUGS BEFORE AND AFTER CAPILLARY PRESSURE TESTS

| Plug ID | Ka (md) (before test) | Ka (md) (after test) |
|---|---|---|
| BA_1A | 517.5 | 517.5 |
| BA_1B | 537.1 | 518.6 |
| BA_1C | 494.9 | 528.1 |
| BA_1D | 505.3 | 505.3 |
| Average | 513.7 | 517.3 |

Table IB-2

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Field | = BEREA | | Air perm | = 517.50 md | | Density diff | = | .834 g/cc |
| Well | = | | Porosity | = 21.20 % | | Rotor Radius | = | 8.60 cm |
| Depth | = | ft | Pore volume | = 3.19 cc | | Wetting angle | = | 0.00 deg |
| Sample | = BA_1A | | Length | = 2.60 cm | | IFT(dynes/cm) | = | 27.10 |

| Data Point | Pc | Sw* | J-Function |
|---|---|---|---|
| 1 | 1.41 | .314 | .566 |
| 2 | 2.51 | .296 | 1.007 |
| 3 | 10.05 | .245 | 4.030 |
| 4 | 22.61 | .215 | 9.067 |
| 5 | 40.20 | .194 | 16.122 |
| 6 | 141.31 | .153 | 56.678 |
| 7 | 251.22 | .137 | 100.763 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Field | = BEREA | | Air perm | = 537.10 md | | Density diff | = | .834 g/cc |
| Well | = | | Porosity | = 21.10 % | | Rotor Radius | = | 8.60 cm |
| Depth | = | ft | Pore volume | = 3.20 cc | | Wetting angle | = | 0.00 deg |
| Sample | = BA_1B | | Length | = 2.58 cm | | IFT(dynes/cm) | = | 27.10 |

| Data Point | Pc | Sw* | J-Function |
|---|---|---|---|
| 1 | 1.41 | .554 | .577 |
| 2 | 2.50 | .491 | 1.026 |
| 3 | 10.01 | .355 | 4.099 |
| 4 | 22.52 | .310 | 9.222 |
| 5 | 40.03 | .291 | 16.395 |
| 6 | 140.73 | .273 | 57.690 |
| 7 | 250.19 | .269 | 102.471 |

Table IB-3

Field = BEREA
Well =
Depth = ft
Sample = BA_1C

Air perm = 494.90 md
Porosity = 21.30 %
Pore volume = 2.96 cc
Length = 2.59 cm

Density diff = .834 g/cc
Rotor Radius = 8.60 cm
Wetting angle = 0.00 deg
IFT(dynes/cm) = 27.10

| Data Point | Pc | Sw* | J-Function |
|---|---|---|---|
| 1 | 1.41 | .508 | .553 |
| 2 | 2.51 | .439 | .983 |
| 3 | 10.04 | .283 | 3.929 |
| 4 | 22.59 | .227 | 8.839 |
| 5 | 40.16 | .203 | 15.715 |
| 6 | 141.18 | .179 | 55.243 |
| 7 | 250.98 | .175 | 98.212 |

Field = BEREA
Well =
Depth = ft
Sample = BA_1D

Air perm = 505.30 md
Porosity = 21.00 %
Pore volume = 3.10 cc
Length = 2.59 cm

Density diff = .834 g/cc
Rotor Radius = 8.60 cm
Wetting angle = 0.00 deg
IFT(dynes/cm) = 27.10

| Data Point | Pc | Sw* | J-Function |
|---|---|---|---|
| 1 | 1.41 | .454 | .561 |
| 2 | 2.51 | .384 | .999 |
| 3 | 10.03 | .239 | 3.996 |
| 4 | 22.57 | .192 | 8.991 |
| 5 | 40.13 | .173 | 15.981 |
| 6 | 141.09 | .154 | 56.184 |
| 7 | 250.82 | .150 | 99.881 |

Table IB-4

| | | |
|---|---|---|
| Field = BEREA | Air perm = 517.50 md | Density diff = .834 g/cc |
| Well = | Porosity = 21.20 % | Rotor Radius = 8.60 cm |
| Depth = ft | Pore volume = 3.19 cc | Wetting angle = 0.00 deg |
| Sample = BA_1A | Length = 2.60 cm | IFT(dynes/cm) = 27.10 |

| Data Point | Sw_avg | Pc(psi) | Swpc |
|---|---|---|---|
| 1 | .6550 | 1.41 | .926 |
| 2 | .4980 | 2.51 | 1.251 |
| 3 | .3410 | 10.05 | 3.427 |
| 4 | .2470 | 22.61 | 5.585 |
| 5 | .2160 | 40.20 | 8.682 |
| 6 | .1840 | 141.31 | 26.001 |
| 7 | .1690 | 251.22 | 42.456 |

| | | |
|---|---|---|
| Field = BEREA | Air perm = 517.50 md | Density diff = .834 g/cc |
| Well = | Porosity = 21.20 % | Rotor Radius = 8.60 cm |
| Depth = ft | Pore volume = 3.19 cc | Wetting angle = 0.00 deg |
| Sample = BA_1A | Length = 2.60 cm | IFT(dynes/cm) = 27.10 |

| Data Point | Pc | Sw* | J-Function |
|---|---|---|---|
| 1 | 1.41 | .459 | .567 |
| 2 | 2.51 | .368 | 1.008 |
| 3 | 10.05 | .224 | 4.031 |
| 4 | 22.61 | .187 | 9.069 |
| 5 | 40.20 | .172 | 16.122 |
| 6 | 141.31 | .159 | 56.679 |
| 7 | 251.22 | .156 | 100.762 |

BROOKS & COREY BUBBLE PRESSURE(Pb) = psi

TABLE IC-1. ROTOR ACCELERATION FOR GAS/OIL AND OIL/BRINE DRAINAGE EXPERIMENTS IN THE BECKMAN L8-55M/P ULTRACENTRIFUGE

| Time (seconds) | to 1000 rpm | to 2000 rpm | to 3000 rpm | to 4000 rpm | to 4000 rpm |
|---|---|---|---|---|---|
| 0. | 0. | 0. | 0. | 0. | 0. |
| 5. | 80. | 120. | 140. | 150. | 300. |
| 10. | 560. | 520. | 540. | 570. | 700. |
| 15. | 880. | 990. | 990. | 1040. | 1110. |
| 20. | 980. | 1410. | 1490. | 1480. | 1590. |
| 25. | 1010. | 1890. | 1990. | 2040. | 2170. |
| 30. | 1020. | 1970. | 2390. | 2670. | 2570. |
| 35. | 1010. | 2010. | 2890. | 3200. | 3140. |
| 40. | 1000. | 2010. | 2980. | - | 3940. |
| 45. | 990. | 2000. | 3000. | 3930. | 4000. |
| 50. | 1000. | 2000. | 3010. | 4000. | - |
| 55. | " | " | 3010. | 4010. | 4010. |
| 60. | " | " | 2990. | 4000. | 4000. |
| 70. | " | " | 3000. | " | " |
| 80. | " | " | " | " | " |
| 90. | " | " | " | " | " |

Figure IC-1

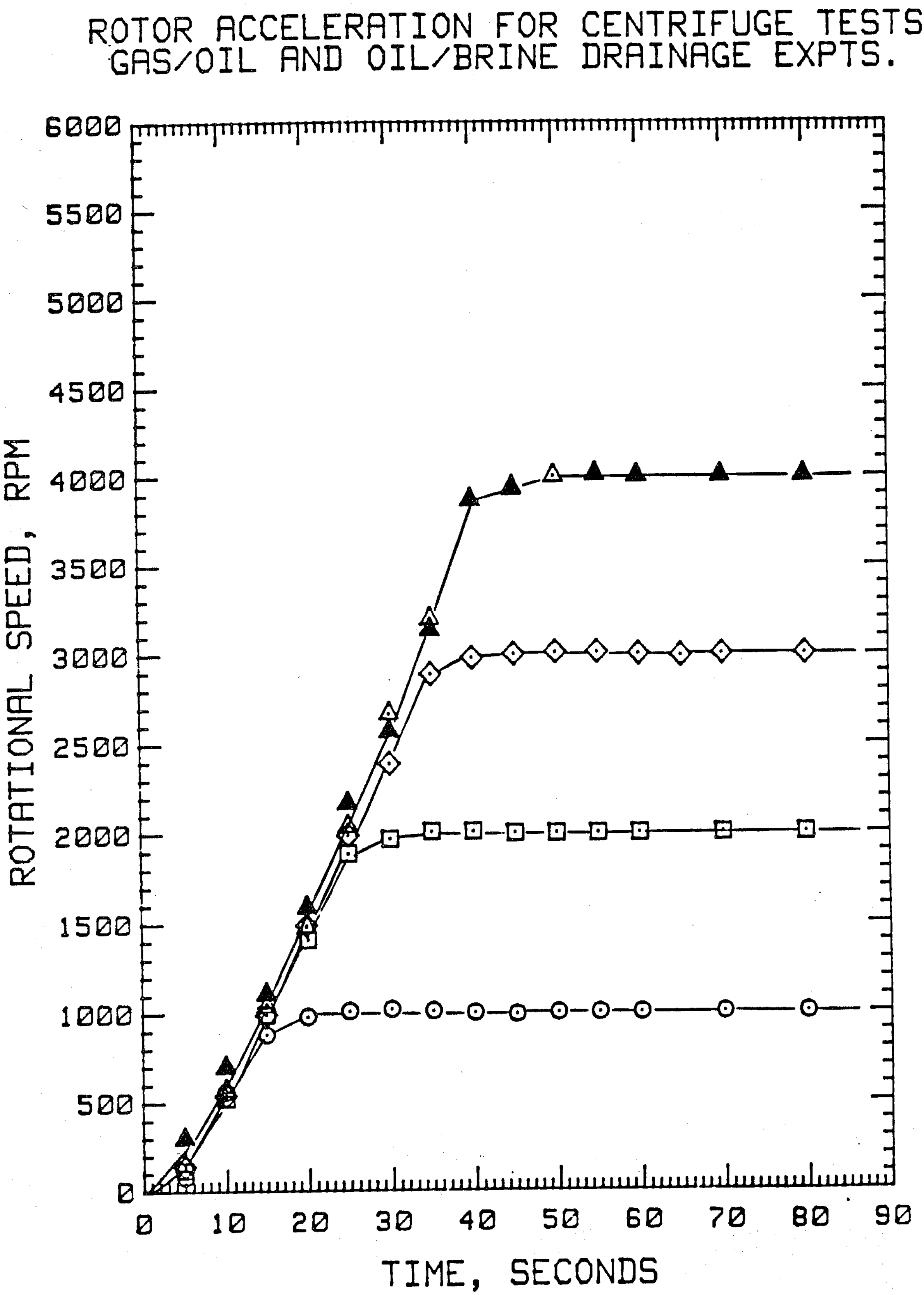
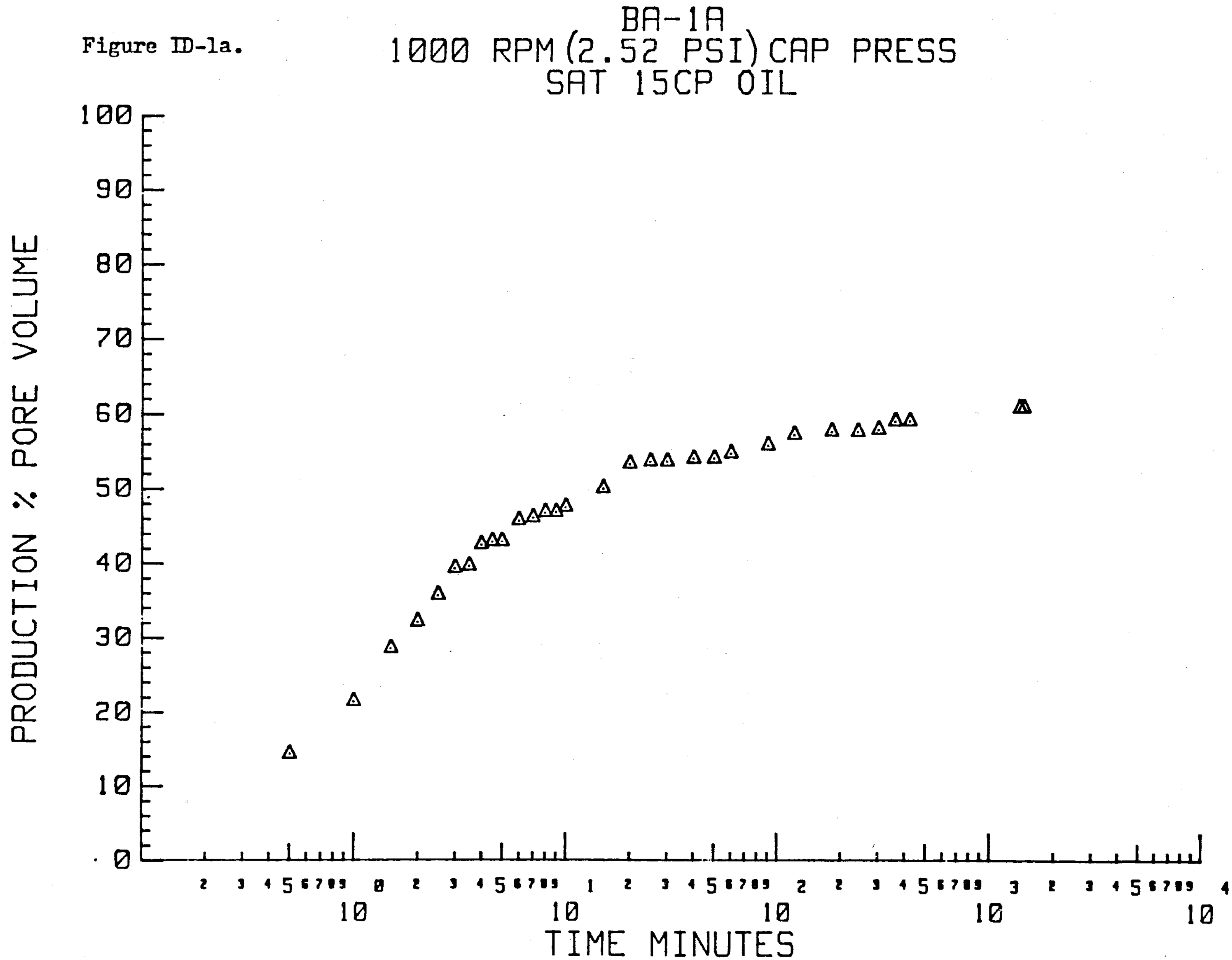

ROTOR ACCELERATION FOR CENTRIFUGE TESTS
GAS/OIL AND OIL/BRINE DRAINAGE EXPTS.
ROTATIONAL SPEED, RPM
6000
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0
10
20
30
40
50
60
70
80
90
TIME, SECONDS

Figure ID-1a.


BA-1A
1000 RPM (2.52 PSI) CAP PRESS
SAT 15CP OIL
PRODUCTION % PORE VOLUME
100
90
80
70
60
50
40
30
20
10
0
TIME MINUTES
10
10
10
10
10

**Core Id = BA-A1** **PRODUCTION DATA** **rpm = 1000**

Table ID-1a

| Pore volume = 2.792 cc | r2 = 8.6 cm | Oil viscosity = 15 cps |
|---|---|---|
| Swi = 0.0% | Length = 2.597 cm | Ift = 27.1 dyne/cm |

| Time (Minutes) | Produced Oil Volume (cc) | % Pore Volume |
|---|---|---|
| 0.00 | 0.00 | 0.00 |
| 0.50 | 0.40 | 14.3 |
| 1.00 | 0.60 | 21.5 |
| 1.50 | 0.80 | 28.6 |
| 2.00 | 0.90 | 32.2 |
| 2.50 | 1.00 | 35.8 |
| 3.00 | 1.10 | 39.4 |
| 3.50 | 1.11 | 39.7 |
| 4.00 | 1.19 | 42.6 |
| 4.50 | 1.20 | 43.0 |
| 5.00 | 1.20 | 43.0 |
| 6.00 | 1.28 | 45.8 |
| 7.00 | 1.29 | 46.2 |
| 8.00 | 1.31 | 46.9 |
| 9.00 | 1.31 | 46.9 |
| 10.0 | 1.33 | 47.6 |
| 15.0 | 1.40 | 50.18 |
| 20.0 | 1.49 | 53.4 |
| 25.0 | 1.50 | 53.7 |
| 30.0 | 1.50 | 53.7 |
| 40.0 | 1.51 | 54.1 |
| 50.0 | 1.51 | 54.1 |
| 60.0 | 1.53 | 54.8 |

Core Id = BA-A1

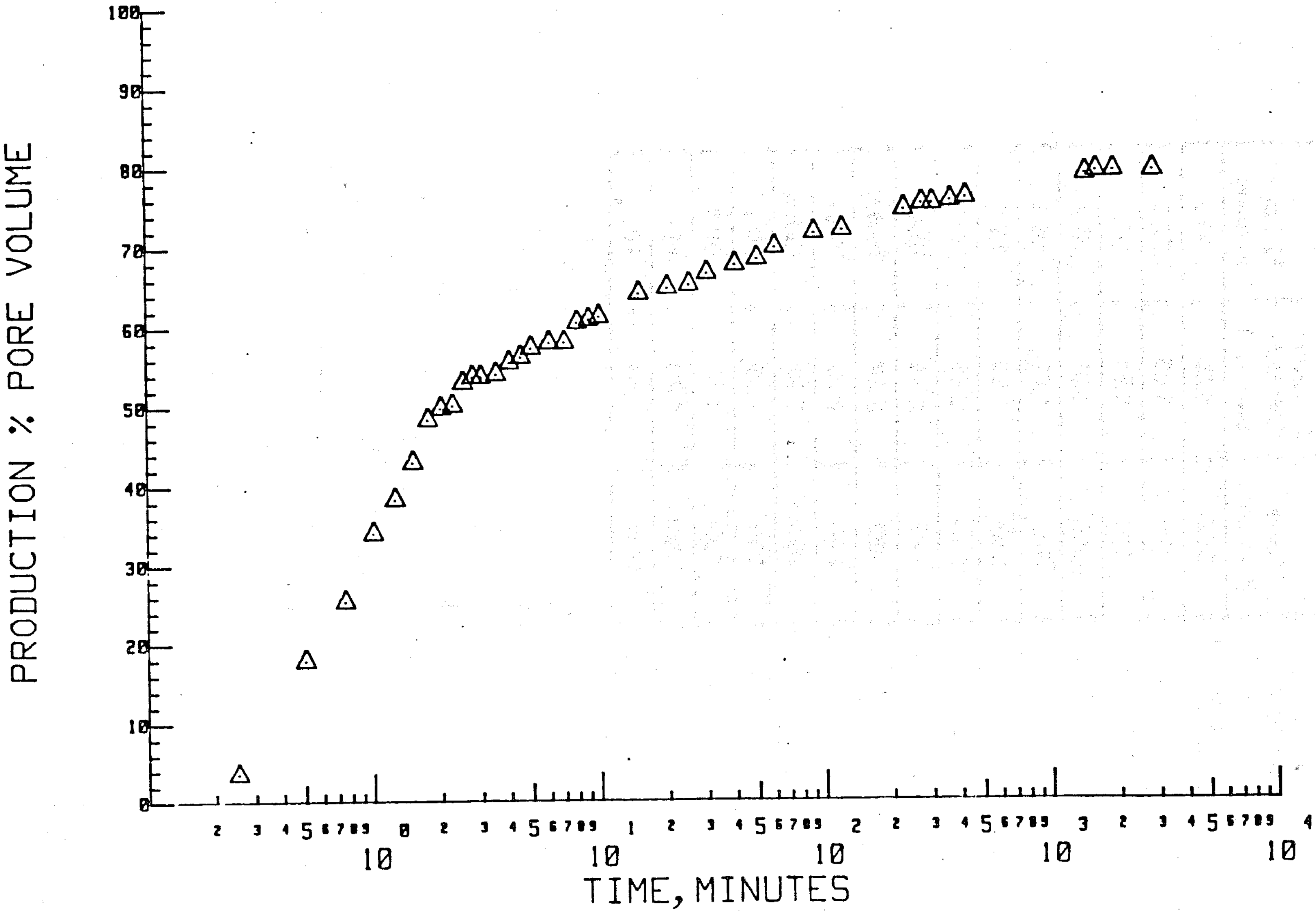
**PRODUCTION DATA**

rpm = 1000

| Time (Minutes) | Produced Oil Volume (cc) | % Pore Volume |
|---|---|---|
| 90.0 | 1.56 | 55.9 |
| 120 | 1.60 | 57.3 |
| 180 | 1.61 | 57.7 |
| 240 | 1.61 | 57.7 |
| 300 | 1.62 | 58.0 |
| 360 | 1.65 | 59.1 |
| 90.0 | 2.15 | 77.01 |
| 120 | 2.19 | 78.45 |
| 180 | 2.20 | 78.81 |
| 240 | 2.20 | 78.81 |
| 300 | 2.23 | 79.88 |
| 360 | 1.65 | 59.1 |
| 420 | 1.65 | 59.1 |
| 1380 | 1.70 | 60.9 |
| 1440 | 1.70 | 60.9 |

Figure ID-1b

BA-1A
2000 RPM (10.07 PSI) CAP PRESS
SAT 15CP OIL



**Core Id = BA-A1** **PRODUCTION DATA** **rpm = 2000**

Table ID-1b

Pore volume = 2.792 cc  r2 = 8.6 cm  Oil viscosity = 15 cps

Swi = 0.0%  Length = 2.597 cm  Ift = 27.1 dyne/cm

| Time (Minutes) | Produced Oil Volume (cc) | % Pore Volume |
|---|---|---|
| 0.00 | 0.00 | 0.00 |
| 0.25 | 0.10 | 3.58 |
| 0.50 | 0.50 | 17.90 |
| 0.75 | 0.71 | 25.43 |
| 1.00 | 0.95 | 34.03 |
| 1.25 | 1.07 | 38.32 |
| 1.50 | 1.20 | 42.98 |
| 1.75 | 1.35 | 48.35 |
| 2.00 | 1.39 | 49.79 |
| 2.25 | 1.40 | 50.14 |
| 2.50 | 1.48 | 53.01 |
| 2.75 | 1.50 | 53.72 |
| 3.00 | 1.50 | 53.72 |
| 3.50 | 1.51 | 54.08 |
| 4.00 | 1.55 | 55.52 |
| 4.50 | 1.57 | 56.23 |
| 5.00 | 1.60 | 57.31 |
| 6.00 | 1.62 | 58.02 |
| 7.00 | 1.69 | 60.53 |
| 9.00 | 1.70 | 60.89 |
| 10.0 | 1.71 | 61.25 |
| 15.0 | 1.79 | 64.11 |
| 20.0 | 1.81 | 64.83 |

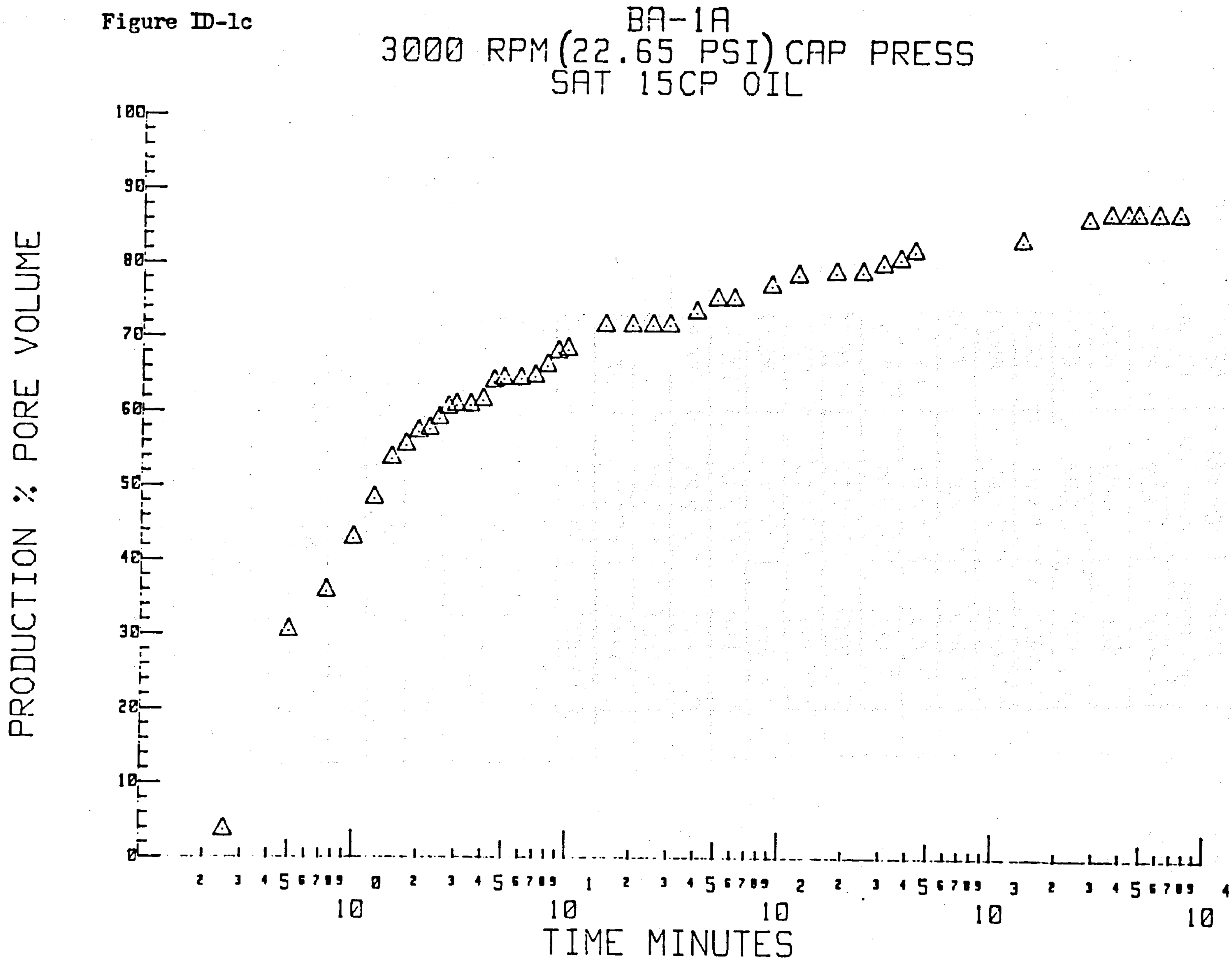
Core Id = BA-A1

**PRODUCTION DATA**

rpm = 2000

| Time (Minutes) | Produced Oil Volume (cc) | % Pore Volume |
|---|---|---|
| 25.0 | 1.82 | 65.19 |
| 30.0 | 1.86 | 66.62 |
| 40.0 | 1.89 | 67.69 |
| 50.0 | 1.91 | 68.41 |
| 60.0 | 1.95 | 69.84 |
| 90.0 | 2.00 | 71.63 |
| 120 | 2.01 | 71.99 |
| 225 | 2.08 | 74.50 |
| 270 | 2.10 | 75.21 |
| 300 | 2.10 | 75.21 |
| 360 | 2.11 | 75.57 |
| 420 | 2.12 | 75.93 |
| 1410 | 2.20 | 78.80 |
| 1580 | 2.21 | 79.15 |
| 1880 | 2.21 | 79.15 |
| 2820 | 2.21 | 79.15 |

Figure III-1c



**Core Id = BA-A1** **PRODUCTION DATA** **rpm = 3000**

Table ID-1c

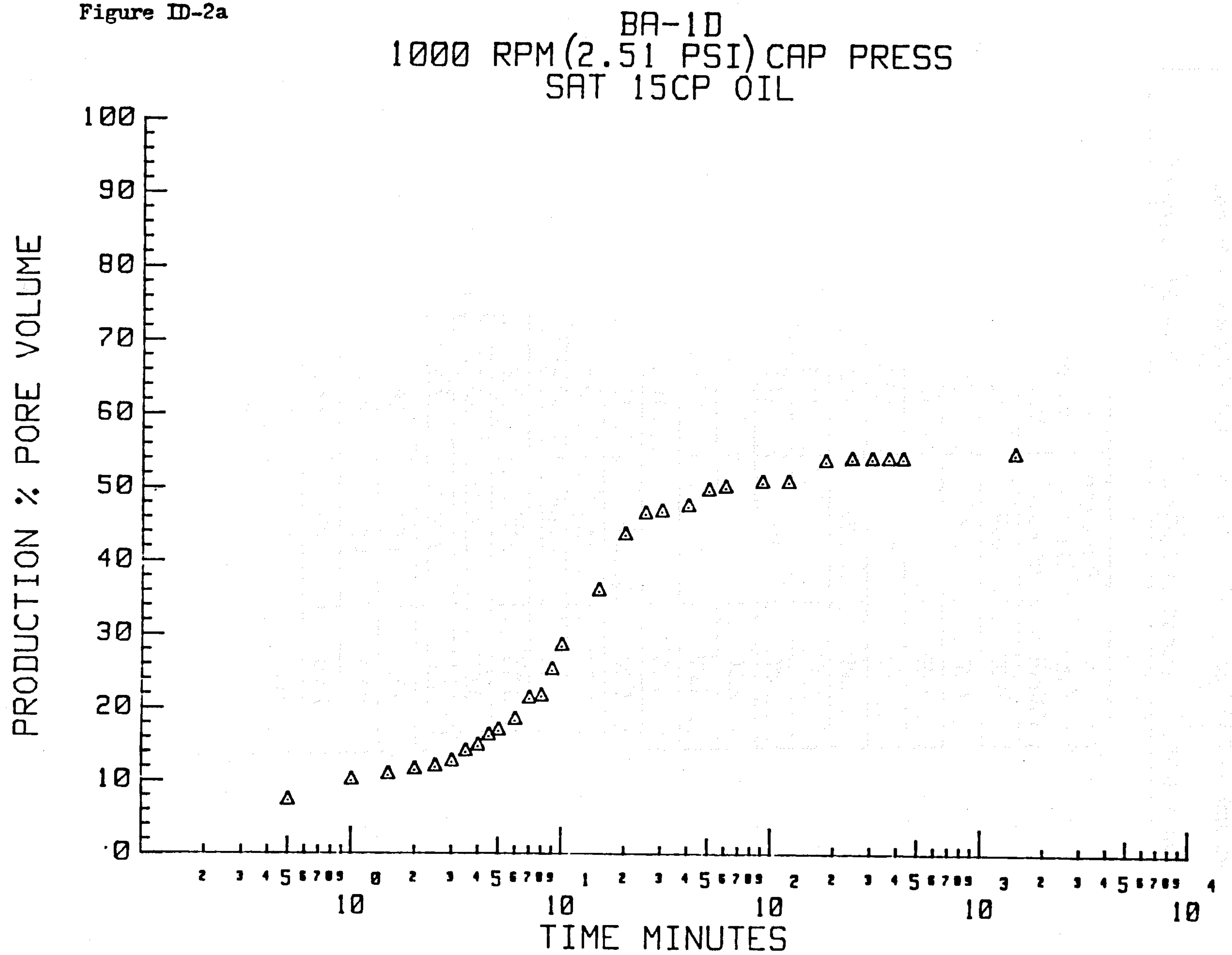
| Pore volume = 2.792 cc | r2 = 8.6 cm | Oil viscosity = 15 cps |
|---|---|---|
| Swi = 0.0% | Length = 2.597 cm | Ift = 27.1 dyne/cm |

| Time (Minutes) | Produced Oil Volume (cc) | % Pore Volume |
|---|---|---|
| 0.00 | 0.00 | 0.00 |
| .25 | 0.10 | 3.58 |
| .50 | 0.85 | 30.45 |
| .75 | 1.00 | 35.82 |
| 1.00 | 1.20 | 42.98 |
| 1.25 | 1.35 | 48.36 |
| 1.50 | 1.50 | 53.73 |
| 1.75 | 1.55 | 55.52 |
| 2.00 | 1.60 | 57.31 |
| 2.25 | 1.61 | 57.67 |
| 2.50 | 1.65 | 59.10 |
| 2.75 | 1.69 | 60.54 |
| 3.00 | 1.70 | 60.89 |
| 3.50 | 1.70 | 60.89 |
| 4.00 | 1.72 | 61.61 |
| 4.50 | 1.79 | 64.12 |
| 5.00 | 1.80 | 64.48 |
| 6.00 | 1.80 | 64.48 |
| 7.00 | 1.81 | 64.84 |
| 8.00 | 1.85 | 66.27 |
| 9.00 | 1.90 | 68.06 |
| 10.0 | 1.91 | 68.42 |
| 15.0 | 2.00 | 71.64 |

**Core Id = BA-A1** **PRODUCTION DATA** **rpm = 3000**

| Time (Minutes) | Produced Oil Volume (cc) | % Pore Volume |
|---|---|---|
| 20.0 | 2.00 | 71.64 |
| 25.0 | 2.00 | 71.64 |
| 30.0 | 2.00 | 71.64 |
| 40.0 | 2.05 | 73.43 |
| 50.0 | 2.10 | 75.22 |
| 60.0 | 2.10 | 75.22 |
| 90.0 | 2.15 | 77.01 |
| 120 | 2.19 | 78.45 |
| 180 | 2.20 | 78.81 |
| 240 | 2.20 | 78.81 |
| 300 | 2.23 | 79.88 |
| 360 | 2.25 | 80.60 |
| 420 | 2.28 | 81.67 |
| 1340 | 2.32 | 83.10 |
| 2780 | 2.40 | 85.97 |
| 3520 | 2.42 | 86.69 |
| 4230 | 2.42 | 86.69 |
| 4740 | 2.42 | 86.69 |
| 5930 | 2.42 | 86.69 |
| 7430 | 2.42 | 86.69 |

Figure ID-2a


BA-1D
1000 RPM (2.51 PSI) CAP PRESS
SAT 15CP OIL
PRODUCTION % PORE VOLUME
100
90
80
70
60
50
40
30
20
10
.0
TIME MINUTES
10
10
10
10
10

Core Id = BA-1D

PRODUCTION DATA

rpm = 1000

Table ID-2a

| | | |
|---|---|---|
| Pore volume = 2.775 cc | r2 = 8.6 cm | Oil viscosity = 15 cps |
| Swi = 0.0% | Length = 2.592 cm | Ift = 27.1 dyne/cm |

| Time (Minutes) | Produced Oil Volume (cc) | % Pore Volume |
|---|---|---|
| 0.00 | 0.00 | 0.00 |
| 0.50 | 0.20 | 7.20 |
| 1.00 | 0.28 | 10.0 |
| 1.50 | 0.30 | 10.8 |
| 2.00 | 0.32 | 11.5 |
| 2.50 | 0.33 | 11.9 |
| 3.00 | 0.35 | 12.6 |
| 3.50 | 0.39 | 14.0 |
| 4.00 | 0.41 | 14.8 |
| 4.50 | 0.45 | 16.2 |
| 5.00 | 0.47 | 16.9 |
| 6.00 | 0.51 | 18.4 |
| 7.00 | 0.59 | 21.3 |
| 8.00 | 0.60 | 21.6 |
| 9.00 | 0.70 | 25.2 |
| 10.0 | 0.79 | 28.5 |
| 15.0 | 1.00 | 36.0 |
| 20.0 | 1.21 | 43.6 |
| 25.0 | 1.29 | 46.5 |
| 30.0 | 1.30 | 46.8 |
| 40.0 | 1.32 | 47.5 |
| 50.0 | 1.38 | 49.7 |
| 60.0 | 1.39 | 50.1 |

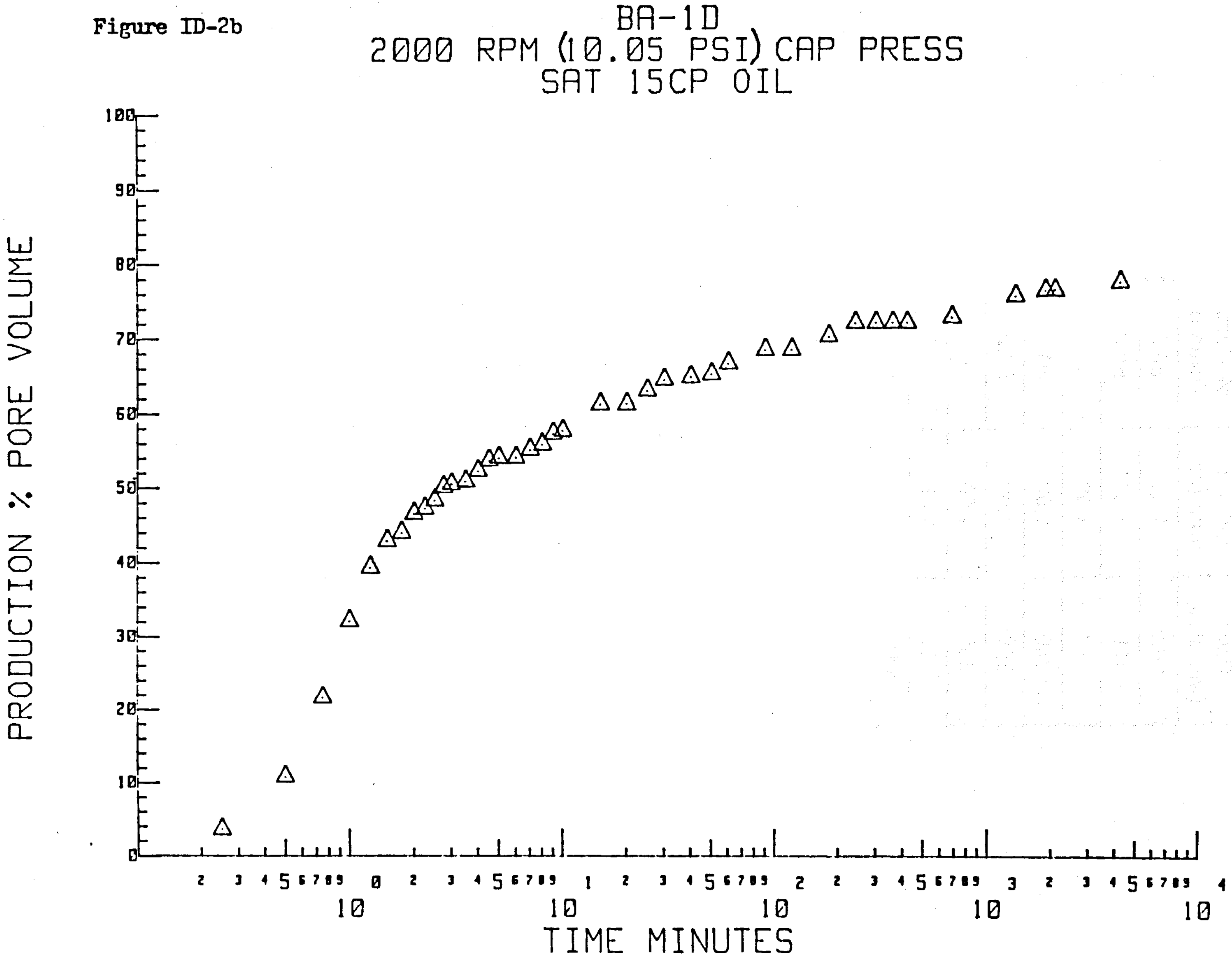
Core Id = BA-1D

PRODUCTION DATA

rpm = 1000

| Time (Minutes) | Produced Oil Volume (cc) | % Pore Volume |
|---|---|---|
| 90.0 | 1.41 | 50.8 |
| 120 | 1.41 | 50.8 |
| 180 | 1.49 | 53.7 |
| 240 | 1.50 | 54.0 |
| 300 | 1.50 | 54.0 |
| 360 | 1.50 | 54.0 |
| 420 | 1.50 | 54.0 |
| 1440 | 1.52 | 54.7 |

Figure ID-2b


BA-1D
2000 RPM (10.05 PSI) CAP PRESS
SAT 15CP OIL
PRODUCTION % PORE VOLUME
0
10
20
30
40
50
60
70
80
90
100
10
10
10
10
10
TIME MINUTES

Core Id = BA-1D

PRODUCTION DATA

rpm = 2000

Table ID-2b

| | | |
|---|---|---|
| Pore volume = 2.775 cc | r2 = 8.6 cm | Oil viscosity = 15 cps |
| Swi = 0.0% | Length = 2.592 cm | Ift = 27.1 dyne/cm |

| Time (Minutes) | Produced Oil Volume (cc) | % Pore Volume |
|---|---|---|
| 0.00 | 0.00 | 0.00 |
| 0.25 | 0.10 | 3.60 |
| 0.50 | 0.30 | 10.8 |
| 0.75 | 0.60 | 21.6 |
| 1.00 | 0.89 | 32.1 |
| 1.25 | 1.09 | 39.3 |
| 1.50 | 1.19 | 42.9 |
| 1.75 | 1.22 | 44.0 |
| 2.00 | 1.29 | 46.5 |
| 2.25 | 1.31 | 47.2 |
| 2.50 | 1.34 | 48.3 |
| 2.75 | 1.39 | 50.1 |
| 3.00 | 1.40 | 50.4 |
| 3.50 | 1.41 | 50.8 |
| 4.00 | 1.45 | 52.2 |
| 4.50 | 1.49 | 53.7 |
| 5.00 | 1.50 | 54.0 |
| 6.00 | 1.50 | 54.0 |
| 7.00 | 1.53 | 55.1 |
| 8.00 | 1.55 | 55.8 |
| 9.00 | 1.59 | 57.3 |
| 10.0 | 1.60 | 57.6 |
| 15.0 | 1.70 | 61.2 |

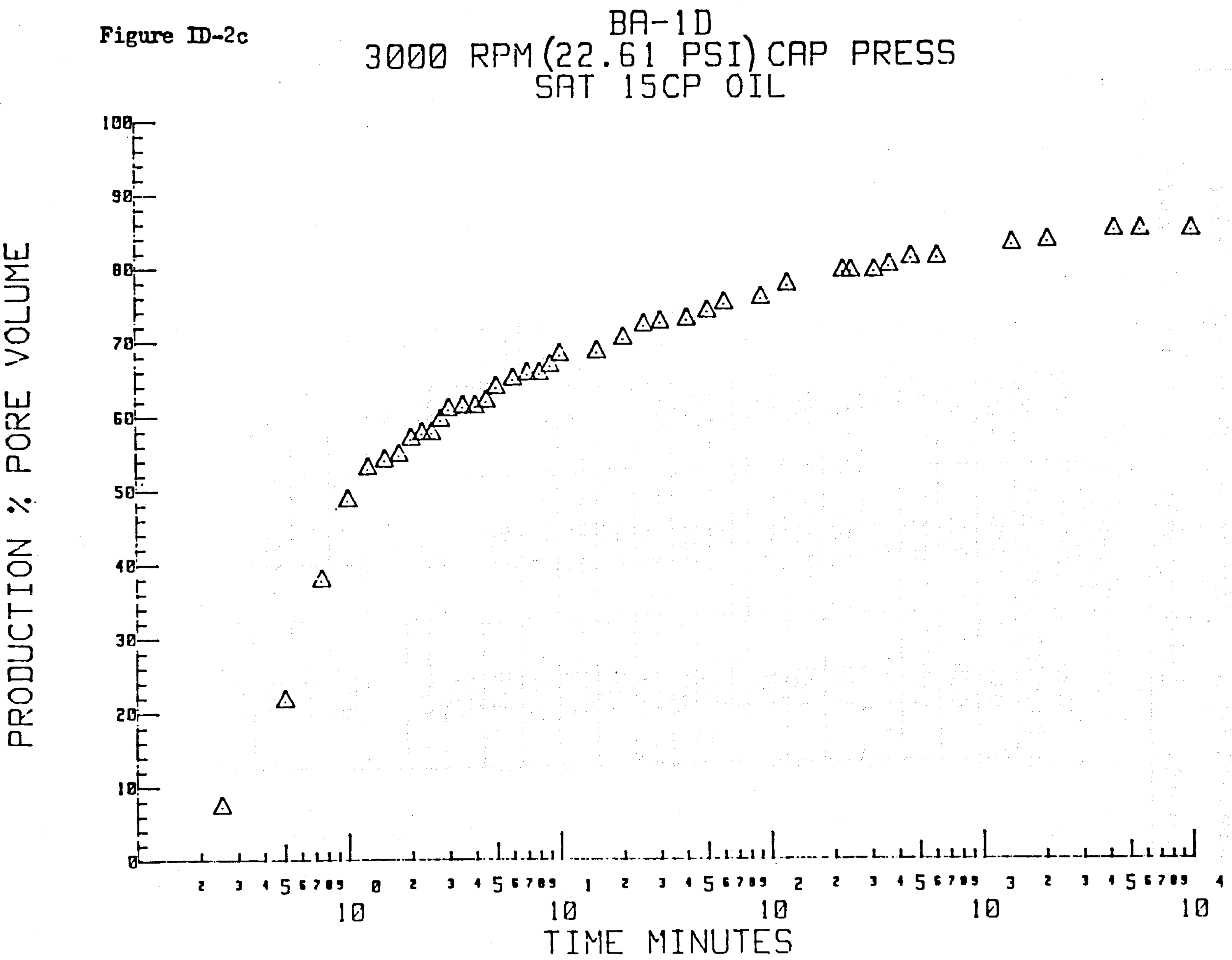
Core Id = BA-1D

**PRODUCTION DATA**

rpm = 2000

| Time (Minutes) | Produced Oil Volume (cc) | % Pore Volume |
|---|---|---|
| 20.0 | 1.70 | 61.2 |
| 25.0 | 1.75 | 63.1 |
| 30.0 | 1.79 | 64.5 |
| 40.0 | 1.80 | 64.9 |
| 50.0 | 1.81 | 65.2 |
| 60.0 | 1.85 | 66.7 |
| 90.0 | 1.90 | 68.5 |
| 120 | 1.90 | 68.5 |
| 180 | 1.95 | 70.3 |
| 240 | 2.00 | 72.1 |
| 300 | 2.00 | 72.1 |
| 360 | 2.00 | 72.1 |
| 420 | 2.00 | 72.1 |
| 684 | 2.02 | 72.8 |
| 1360 | 2.10 | 77.7 |
| 1890 | 2.12 | 76.4 |
| 2100 | 2.12 | 76.4 |
| 2830 | 2.15 | 77.5 |
| 4240 | 2.15 | 77.5 |

Figure ID-2c


BA-1D
3000 RPM (22.61 PSI) CAP PRESS
SAT 15CP OIL
PRODUCTION % PORE VOLUME
TIME MINUTES
0
10
20
30
40
50
60
70
80
90
100

Core Id = BA-1D

PRODUCTION DATA

Table ID-2c

rpm = 3000

| | | |
|---|---|---|
| Pore volume = 2.775 cc | r2 = 8.6 cm | Oil viscosity = 15 cps |
| Swi = 0.0% | Length = 2.592 cm | Ift = 27.1 dyne/cm |

| Time (Minutes) | Produced Oil Volume (cc) | % Pore Volume |
|---|---|---|
| 0.00 | 0.00 | 0.00 |
| 0.25 | 0.20 | 7.21 |
| 0.50 | 0.60 | 21.6 |
| 0.75 | 1.05 | 37.8 |
| 1.00 | 1.35 | 48.7 |
| 1.25 | 1.47 | 53.0 |
| 1.50 | 1.50 | 54.1 |
| 1.75 | 1.52 | 54.8 |
| 2.00 | 1.58 | 57.0 |
| 2.25 | 1.60 | 57.7 |
| 2.50 | 1.60 | 57.7 |
| 2.75 | 1.65 | 59.5 |
| 3.00 | 1.69 | 60.9 |
| 3.50 | 1.70 | 61.3 |
| 4.00 | 1.70 | 61.3 |
| 4.50 | 1.72 | 62.0 |
| 5.00 | 1.77 | 63.8 |
| 6.00 | 1.80 | 64.9 |
| 7.00 | 1.82 | 65.6 |
| 8.00 | 1.82 | 65.6 |
| 9.00 | 1.85 | 66.7 |
| 10.0 | 1.89 | 68.1 |
| 15.0 | 1.90 | 68.5 |

**Core Id = BA-1D** **PRODUCTION DATA** **rpm = 3000**

| Time (Minutes) | Produced Oil Vol- ume (cc) | % Pore Volume |
|---|---|---|
| 20.0 | 1.95 | 70.3 |
| 25.0 | 2.00 | 72.1 |
| 30.0 | 2.01 | 72.4 |
| 40.0 | 2.02 | 72.8 |
| 50.0 | 2.05 | 73.9 |
| 60.0 | 2.08 | 75.0 |
| 90.0 | 2.10 | 75.7 |
| 120 | 2.15 | 77.5 |
| 220 | 2.20 | 79.3 |
| 240 | 2.20 | 79.3 |
| 309 | 2.20 | 79.3 |
| 364 | 2.20 | 80.0 |
| 460 | 2.25 | 81.1 |
| 610 | 2.25 | 81.1 |
| 1380 | 2.30 | 82.9 |
| 2040 | 2.31 | 83.3 |
| 2820 | 2.32 | 83.6 |
| 4260 | 2.35 | 84.7 |
| 5700 | 2.35 | 84.7 |
| 10000 | 2.35 | 84.7 |

SECTION II

TABLE IIA-1. CORE AND FLUID PROPERTIES FOR OIL DRAINAGE GLYCEROL/BRINE SATURATED BEREA CORE BA-2

| | | |
|---|---|---|
| FIELD NAME (OPTIONAL) | : | |
| WELL NUMBER (OPTIONAL) | : | BEREA |
| CORE DEPTH (OPTIONAL) | : | Feet |
| CORE I.D. (OPTIONAL) | : | BA-2 |
| OIL VISCOSITY | = | 7.12 cp |
| GAS VISCOSITY | = | 1.5 cp |
| OIL DENSITY | = | 1.147 g/cc |
| GAS DENSITY | = | .863 g/cc |
| DPT FLUID DENSITY | = | 0 g/cc |
| INITIAL WATER SATURATION | = | 0 % |
| BASE PERMEABILITY | = | 390 md |
| PORE VOLUME | = | 12.02 cc |
| CORE LENGTH | = | 11.19 cm |
| CORE DIAMETER | = | 2.53 cm |
| POROSITY (OPTIONAL) | = | 21.4 % |
| AIR PERM (OPTIONAL) | = | 450 md |
| FLOW RATE | = | 1 cc/min |
| DEAD VOLUME | = | 0 cc |
| DOWNSTREAM DEAD VOLUME | = | 0 cc |
| LEAK RATE | = | 0 cc/min |
| AXIS ORIENTATION | = | 0 degrees |
| TEST TEMPERATURE (OPTIONAL) | = | 75 degrees F |
| AVERAGE OVERBURDEN PRESSURE (OPTIONAL) | = | 500 psi |

TABLE IIA-2. GLYCEROL/BRINE-OIL DRAINAGE PRODUCTION DATA FOR BEREA CORE BA-2

| POINT NUMBER | PRESSURE DROP (psi) | PROD. (cc) | TIME (minutes) |
|---|---|---|---|
| 1 | 9.8 | 2.4 | 2.42 |
| 2 | 9.5 | 3.8 | 6.1 |
| 3 | 9.4 | 5 | 10.83 |
| 4 | 9.1 | 5.2 | 11.75 |
| 5 | 8.6 | 5.6 | 13.67 |
| 6 | 8.5 | 6 | 15.58 |
| 7 | 7.9 | 6.2 | 19.5 |
| 8 | 7.5 | 6.4 | 23 |
| 9 | 7.3 | 6.5 | 26 |
| 10 | 7.2 | 6.6 | 30 |
| 11 | 7 | 6.7 | 34.1 |
| 12 | 6.8 | 6.8 | 39.1 |
| 13 | 6.7 | 6.9 | 42 |
| 14 | 6.6 | 7 | 46.05 |
| 15 | 6.6 | 7.1 | 56.2 |
| 16 | 6.5 | 7.2 | 63.5 |
| 17 | 6.4 | 7.3 | 76.4 |
| 18 | 5.6 | 7.4 | 92.34 |
| 19 | 5.4 | 7.45 | 123 |
| 20 | 5 | 7.7 | 219 |
| 21 | 4.9 | 7.75 | 300.1 |
| 22 | 4.8 | 7.85 | 318.7 |
| 23 | 4.8 | 7.95 | 376.2 |
| 24 | 4.6 | 8 | 466 |
| 25 | 4.6 | 8 | 484 |

Figure IIA-1

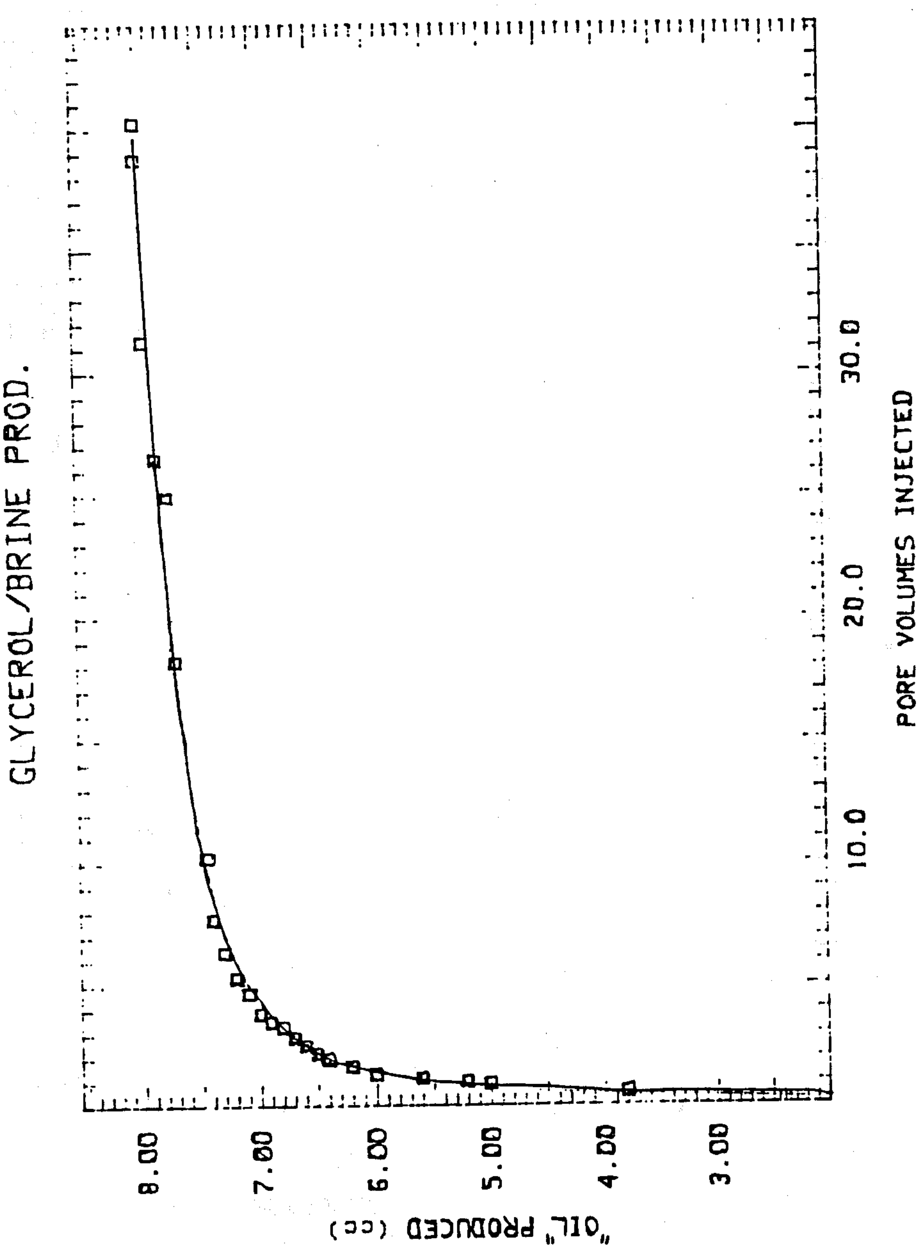

GLYCEROL/BRINE PROD.
"OIL" PRODUCED (cc)
8.00
7.00
6.00
5.00
4.00
3.00
PORE VOLUMES INJECTED
10.0
20.0
30.0

Figure IIA-2

OIL DISPLACING GLYCEROL/BRINE - CORE BA-2

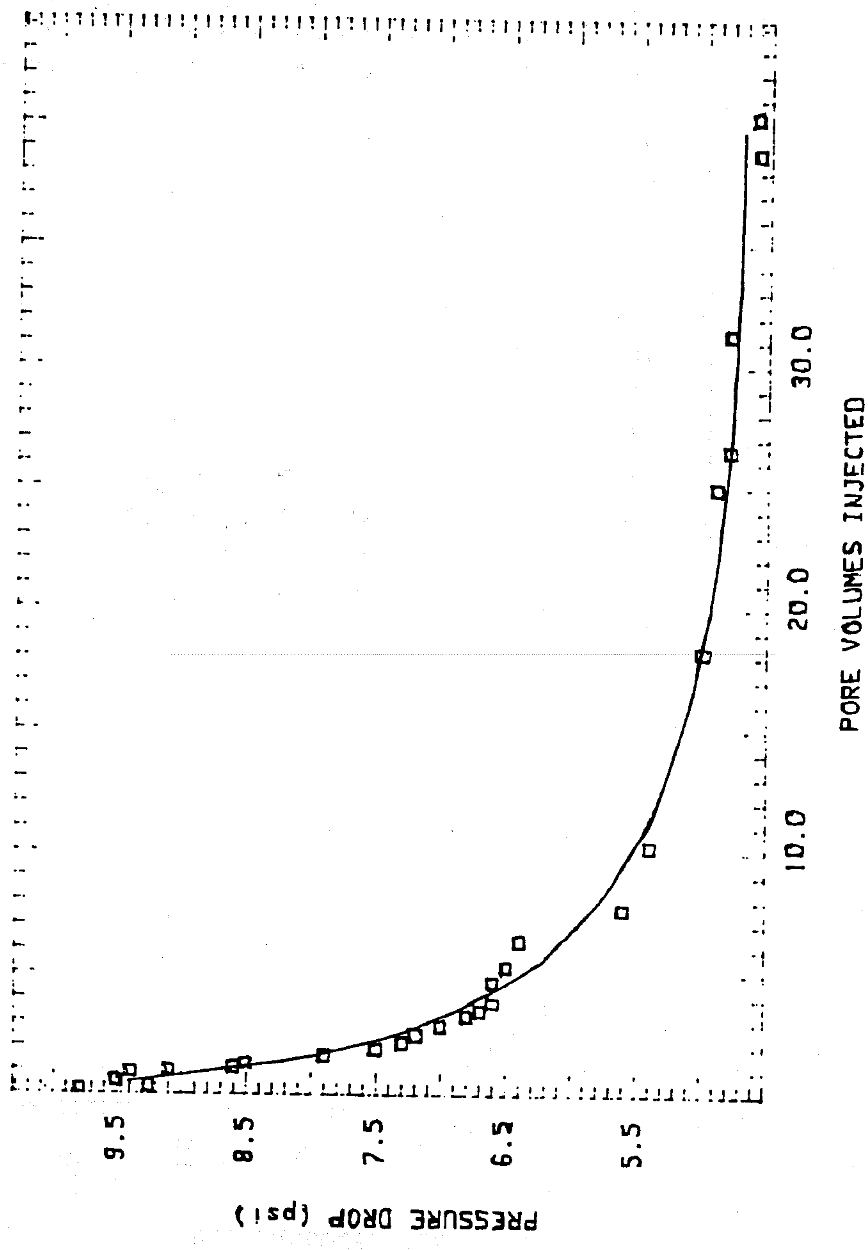


Figure IIB-1

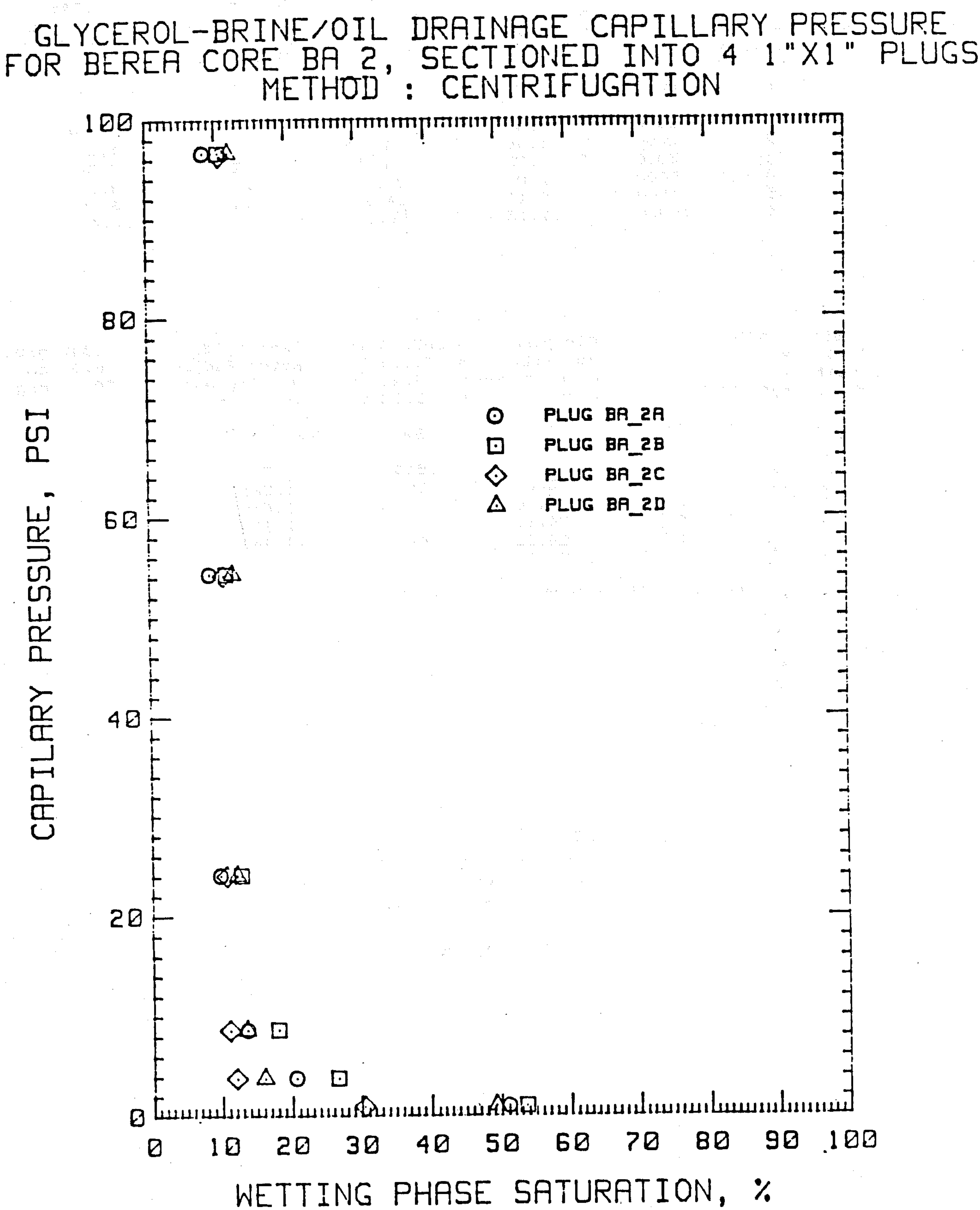

GLYCEROL-BRINE/OIL DRAINAGE CAPILLARY PRESSURE
FOR BEREA CORE BA 2, SECTIONED INTO 4 1"X1" PLUGS
METHOD : CENTRIFUGATION
CAPILARY PRESSURE, PSI
100
80
60
40
20
0
PLUG BA_2A
PLUG BA_2B
PLUG BA_2C
PLUG BA_2D
0
10
20
30
40
50
60
70
80
90
100
WETTING PHASE SATURATION, %

Table IIB-2a

| | | | | | |
|---|---|---|---|---|---|
| Field = BEREA | | Air perm = 368.70 md | | Density diff = .345 g/cc | |
| Well = | | Porosity = 20.14 % | | Rotor Radius = 8.60 cm | |
| Depth = ft | | Pore volume = 2.41 cc | | Wetting angle = 30.00 deg | |
| Sample = BA_2A | | Length = 2.38 cm | | IFT(dynes/cm) = 33.30 | |

| Reading | RPM | ML OUT | Pc | Sw(Avg) | (Sw)(Pc) |
|---|---|---|---|---|---|
| 1 | 1000 | .40 | .966 | .834 | .806 |
| 2 | 2000 | 1.40 | 3.865 | .419 | 1.620 |
| 3 | 3000 | 1.75 | 8.696 | .274 | 2.381 |
| 4 | 5000 | 2.00 | 24.155 | .170 | 4.109 |
| 5 | 7500 | 2.10 | 54.348 | .129 | 6.991 |
| 6 | 10000 | 2.15 | 96.619 | .108 | 10.424 |



| | | |
|---|---|---|
| Field = BEREA | Air perm = 368.70 md | Density diff = .345 g/cc |
| Well = | Porosity = 20.14 % | Rotor Radius = 8.60 cm |
| Depth = ft | Pore volume = 2.41 cc | Wetting angle = 30.00 deg |
| Sample = BA_2A | Length = 2.38 cm | IFT(dynes/cm) = 33.30 |



| Data Point | Pc | Sw* | J-Function |
|---|---|---|---|
| 1 | .97 | .510 | .315 |
| 2 | 3.86 | .205 | 1.261 |
| 3 | 8.70 | .136 | 2.838 |
| 4 | 24.15 | .099 | 7.884 |
| 5 | 54.35 | .087 | 17.740 |
| 6 | 96.62 | .083 | 31.537 |

BROOKS & COREY BUBBLE PRESSURE(Pb) = psi

Table IIB-2b

| | | | |
|---|---|---|---|
| Field = BEREA | Air perm = 361.00 md | Density diff = .345 g/cc |
| Well = | Porosity = 20.27 % | Rotor Radius = 8.60 cm |
| Depth = ft | Pore volume = 2.43 cc | Wetting angle = 30.00 deg |
| Sample = BA_2B | Length = 2.38 cm | IFT(dynes/cm) = 33.30 |

| Reading | RPM | ML OUT | Pc | Sw(Avg) | (Sw)(Pc) |
|---|---|---|---|---|---|
| 1 | 1000 | .30 | .966 | .877 | .847 |
| 2 | 2000 | 1.40 | 3.865 | .424 | 1.638 |
| 3 | 3000 | 1.70 | 8.696 | .300 | 2.612 |
| 4 | 5000 | 1.90 | 24.155 | .218 | 5.268 |
| 5 | 7500 | 2.05 | 54.348 | .156 | 8.499 |
| 6 | 10000 | 2.10 | 96.619 | .136 | 13.121 |

| | | |
|---|---|---|
| Field = BEREA | Air perm = 361.00 md | Density diff = .345 g/cc |
| Well = | Porosity = 20.27 % | Rotor Radius = 8.60 cm |
| Depth = ft | Pore volume = 2.43 cc | Wetting angle = 30.00 deg |
| Sample = BA_2B | Length = 2.38 cm | IFT(dynes/cm) = 33.30 |

| Data Point | Pc | Sw* | J-Function |
|---|---|---|---|
| 1 | .97 | .536 | .311 |
| 2 | 3.86 | .266 | 1.244 |
| 3 | 8.70 | .180 | 2.800 |
| 4 | 24.15 | .129 | 7.776 |
| 5 | 54.35 | .111 | 17.497 |
| 6 | 96.62 | .105 | 31.106 |

BROOKS & COREY BUBBLE PRESSURE(Pb) = . psi

Table IIB-2c

| | | |
|---|---|---|
| Field = BEREA | Air perm = 359.70 md | Density diff = .345 g/cc |
| Well = | Porosity = 20.48 % | Rotor Radius = 8.60 cm |
| Depth = ft | Pore volume = 2.44 cc | Wetting angle = 30.00 deg |
| Sample = BA_2C | Length = 2.37 cm | IFT(dynes/cm) = 33.30 |

| Reading | RPM | ML OUT | Pc | Sw(Avg) | (Sw)(Pc) |
|---|---|---|---|---|---|
| 1 | 1000 | .50 | .963 | .795 | .765 |
| 2 | 2000 | 1.50 | 3.851 | .385 | 1.484 |
| 3 | 3000 | 1.85 | 8.665 | .242 | 2.095 |
| 4 | 5000 | 2.10 | 24.070 | .139 | 3.354 |
| 5 | 7500 | 2.15 | 54.157 | .119 | 6.437 |
| 6 | 10000 | 2.15 | 96.278 | .119 | 11.443 |

| | | |
|---|---|---|
| Field = BEREA | Air perm = 359.70 md | Density diff = .345 g/cc |
| Well = | Porosity = 20.48 % | Rotor Radius = 8.60 cm |
| Depth = ft | Pore volume = 2.44 cc | Wetting angle = 30.00 deg |
| Sample = BA_2C | Length = 2.37 cm | IFT(dynes/cm) = 33.30 |

| Data Point | Pc | Sw* | J-Function |
|---|---|---|---|
| 1 | .96 | .304 | .308 |
| 2 | 3.85 | .120 | 1.231 |
| 3 | 8.67 | .111 | 2.770 |
| 4 | 24.07 | .108 | 7.695 |
| 5 | 54.16 | .107 | 17.314 |
| 6 | 96.28 | .107 | 30.781 |

BROOKS & COREY BUBBLE PRESSURE(Pb) = psi

Table IIB-2d

| | | |
|---|---|---|
| Field = BEREA | Air perm = 360.80 md | Density diff = .345 g/cc |
| Well = | Porosity = 20.32 % | Rotor Radius = 8.60 cm |
| Depth = ft | Pore volume = 2.43 cc | Wetting angle = 30.00 deg |
| Sample = BA_2D | Length = 2.38 cm | IFT(dynes/cm) = 33.30 |

| Reading | RPM | ML OUT | Pc | Sw(Avg) | (Sw)(Pc) |
|---|---|---|---|---|---|
| 1 | 1000 | .40 | .966 | .835 | .807 |
| 2 | 2000 | 1.40 | 3.865 | .424 | 1.638 |
| 3 | 3000 | 1.75 | 8.696 | .280 | 2.433 |
| 4 | 5000 | 2.00 | 24.155 | .177 | 4.274 |
| 5 | 7500 | 2.10 | 54.348 | .136 | 7.381 |
| 6 | 10000 | 2.10 | 96.619 | .136 | 13.121 |



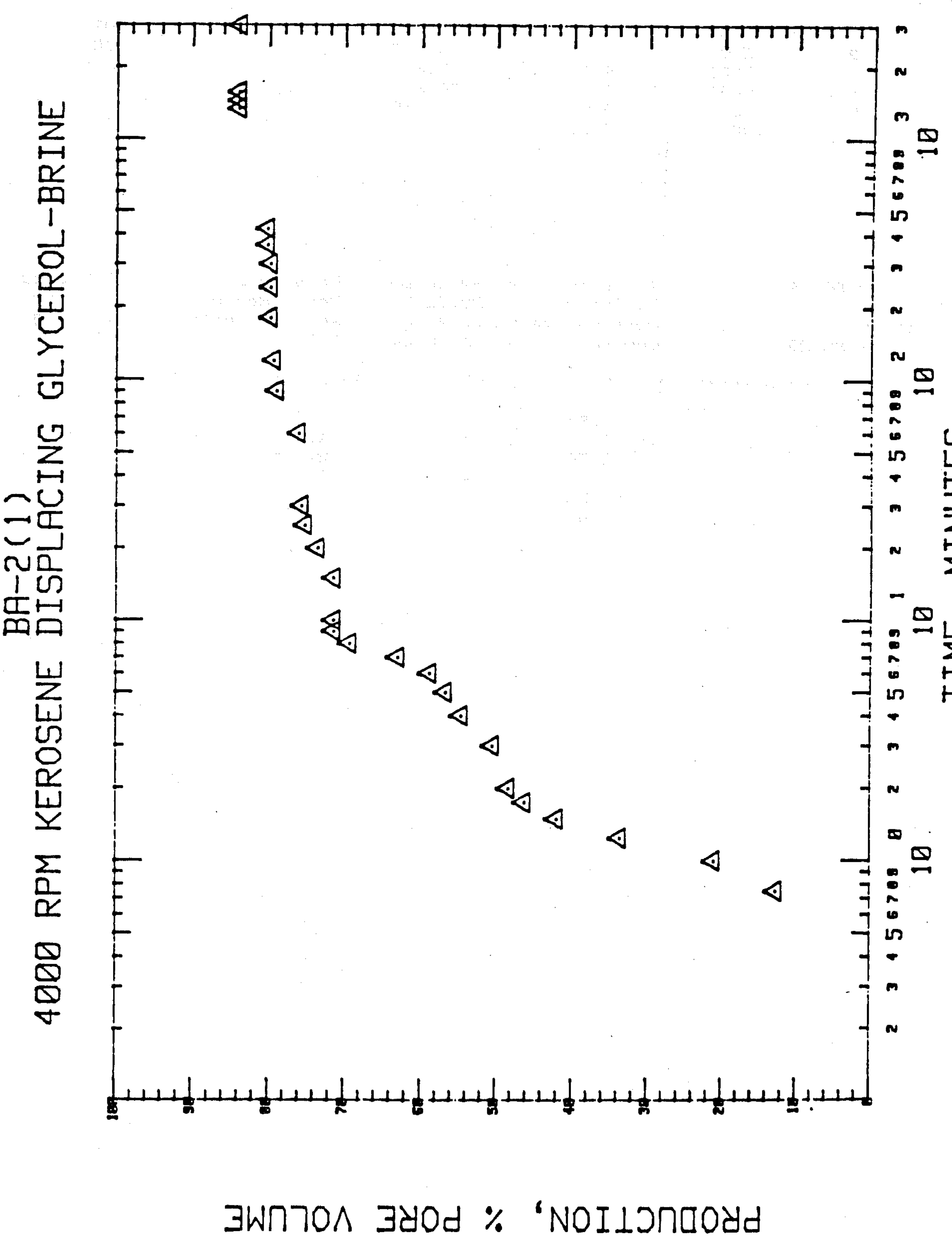
| | | |
|---|---|---|
| Field = BEREA | Air perm = 360.80 md | Density diff = .345 g/cc |
| Well = | Porosity = 20.32 % | Rotor Radius = 8.60 cm |
| Depth = ft | Pore volume = 2.43 cc | Wetting angle = 30.00 deg |
| Sample = BA_2D | Length = 2.38 cm | IFT(dynes/cm) = 33.30 |



| Data Point | Pc | Sw* | J-Function |
|---|---|---|---|
| 1 | .97 | .492 | .311 |
| 2 | 3.86 | .160 | 1.242 |
| 3 | 8.70 | .135 | 2.795 |
| 4 | 24.15 | .123 | 7.765 |
| 5 | 54.35 | .120 | 17.471 |
| 6 | 96.62 | .119 | 31.059 |

BROOKS & COREY BUBBLE PRESSURE(Pb) = psi

Figure IIC-1


BA-2(1)
4000 RPM KEROSENE DISPLACING GLYCEROL-BRINE
TIME, MINUTES
PRODUCTION, % PORE VOLUME

Core Id = BA-2(1) **PRODUCTION DATA** rpm = 4000

Table IIC-1

| | | |
|---|---|---|
| Pore volume = 2.383 cc | r2 = 8.6 cm | Oil viscosity = 1.5 cps |
| Wetting Angle = 30.0 deg | Length = 2.38 cm | Ift = 28.8 dyne/cm |

| Time (Minutes) | Produced Oil Vol- ume (cc) | % Pore Volume |
|---|---|---|
| 0.00 | 0.00 | 0.00 |
| 0.25 | 0.10 | 4.20 |
| 0.50 | 0.30 | 12.6 |
| 0.75 | 0.30 | 12.6 |
| 1.00 | 0.50 | 21.0 |
| 1.25 | 0.80 | 33.6 |
| 1.50 | 1.00 | 42.0 |
| 1.75 | 1.10 | 46.2 |
| 2.00 | 1.15 | 48.2 |
| 3.00 | 1.20 | 50.4 |
| 4.00 | 1.30 | 54.6 |
| 5.00 | 1.35 | 56.6 |
| 6.00 | 1.40 | 58.7 |
| 7.00 | 1.50 | 62.9 |
| 8.00 | 1.65 | 69.2 |
| 9.00 | 1.70 | 71.3 |
| 10.0 | 1.70 | 71.3 |
| 15.0 | 1.71 | 71.3 |
| 20.0 | 1.75 | 73.4 |
| 25.0 | 1.79 | 75.1 |
| 30.0 | 1.80 | 75.5 |
| 60.0 | 1.81 | 76.0 |
| 90.0 | 1.88 | 78.9 |
| 120 | 1.89 | 79.3 |

Core Id = BA-2(1)

PRODUCTION DATA

rpm = 4000

| Time (Minutes) | Produced Oil Volume (cc) | % Pore Volume |
|---|---|---|
| 180 | 1.90 | 79.7 |
| 240 | 1.90 | 79.7 |
| 300 | 1.90 | 79.7 |
| 360 | 1.91 | 80.2 |
| 420 | 1.91 | 80.2 |
| 1330 | 2.00 | 83.9 |
| 1440 | 2.00 | 83.9 |
| 1560 | 2.00 | 83.9 |
| 2970 | 2.00 | 83.9 |

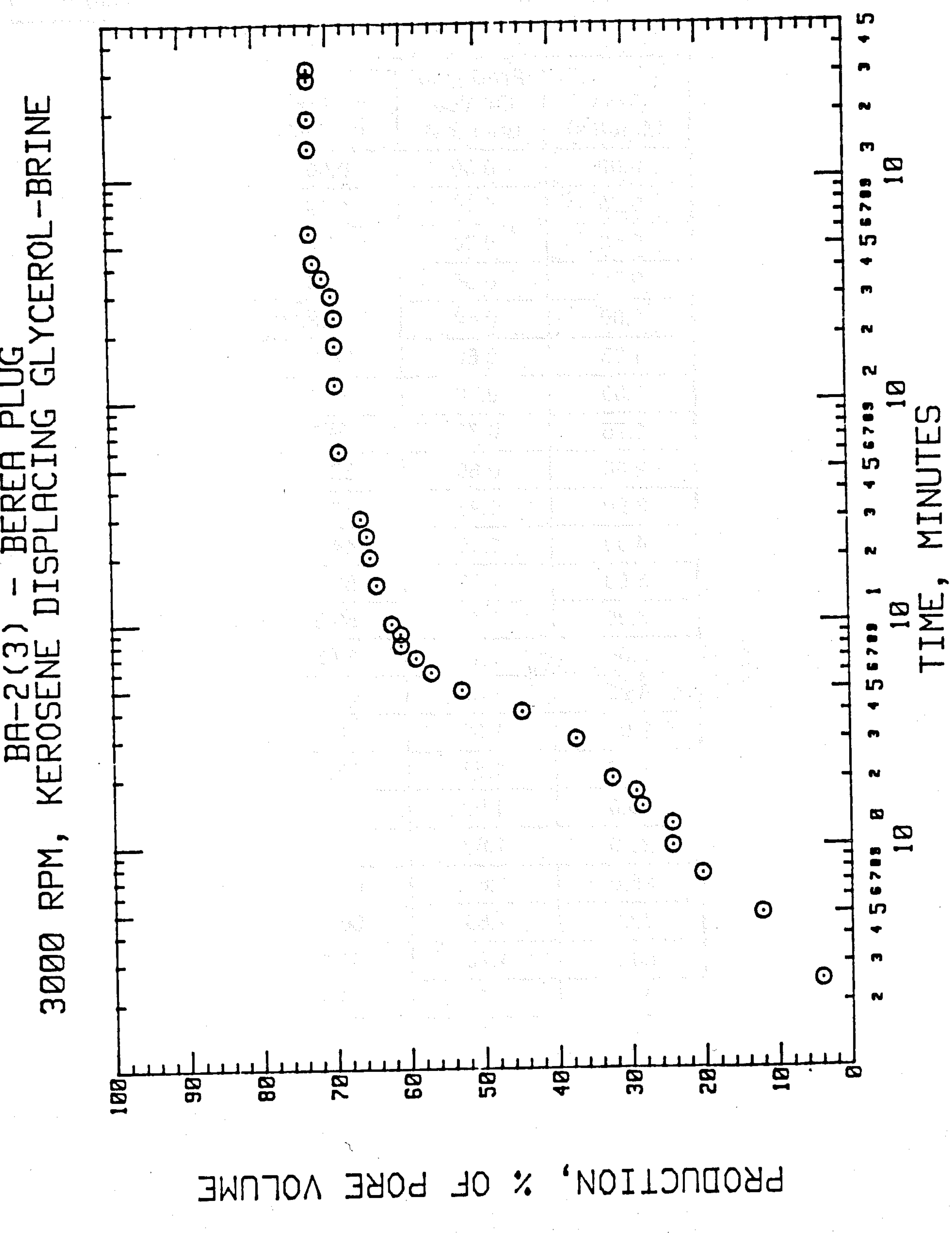

BA-2(3) - BEREA PLUG
3000 RPM, KEROSENE DISPLACING GLYCEROL-BRINE
TIME, MINUTES
PRODUCTION, % OF PORE VOLUME

Figure IIC-2

Core Id = BA-2(3)

PRODUCTION DATA

rpm = 3000

Table IIC-2

| | | |
|---|---|---|
| Pore volume = 2.465 cc | r2 = 8.6 cm | Oil viscosity = 1.5 cps |
| Wetting Angle = 30.0 deg | Length = 2.37 cm | Ift = 28.8 dyne/cm |

| Time (Minutes) | Produced Oil Vol-ume (cc) | % Pore Volume |
|---|---|---|
| 0.00 | 0.00 | 0.00 |
| 0.25 | 0.10 | 4.06 |
| 0.50 | 0.30 | 12.2 |
| 0.75 | 0.50 | 20.3 |
| 1.00 | 0.60 | 24.3 |
| 1.25 | 0.60 | 24.3 |
| 1.50 | 0.70 | 28.4 |
| 1.75 | 0.72 | 29.2 |
| 2.00 | 0.80 | 32.4 |
| 3.00 | 0.92 | 37.3 |
| 4.00 | 1.10 | 44.6 |
| 5.00 | 1.30 | 52.7 |
| 6.00 | 1.40 | 56.8 |
| 7.00 | 1.45 | 58.8 |
| 8.00 | 1.50 | 60.8 |
| 9.00 | 1.50 | 60.8 |
| 10.0 | 1.53 | 62.1 |
| 15.0 | 1.59 | 64.5 |
| 20.0 | 1.60 | 64.9 |
| 25.0 | 1.61 | 65.3 |
| 30.0 | 1.63 | 66.1 |
| 60.0 | 1.70 | 69.0 |
| 120 | 1.71 | 69.4 |
| 180 | 1.71 | 69.4 |

**Core Id = BA-2(3)** **PRODUCTION DATA** **rpm = 3000**

| Time (Minutes) | Produced Oil Volume (cc) | % Pore Volume |
|---|---|---|
| 240 | 1.71 | 69.4 |
| 300 | 1.72 | 69.8 |
| 360 | 1.75 | 71.1 |
| 420 | 1.78 | 72.2 |
| 570 | 1.79 | 72.6 |
| 1370 | 1.79 | 72.6 |
| 1880 | 1.79 | 72.6 |
| 2800 | 1.79 | 72.6 |
| 3130 | 1.79 | 72.6 |

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