Rev.Téc.Ing., Univ.Zulia
Vol.4, N°s.1 y 2, 1981

NUMERICALLY CONTROLLED EXPERIMENTS ON INITIAL PARAMETERS FOR STRESS-SENSITIVE RESERVOIRS

(Recibido el 19 de Enero de 1981)

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ABSTRACT

This paper presents results of a study investigating the sensitivity of reservoir pressure to the parameters of stress-sensitive reservoirs. Stress-sensitive reservoirs are reservoirs with rock properties that depend on the effective stress on the reservoir rocks. The pressure sensitivity was studied by performing numerically controlled experiments in which the parameters of interest were varied, either singly or jointly, and the effect of the variations on the reservoir pressure was observed. A criterion function which characterized the difference between the calculated pressures using a certain parameter value and an assumed base value for the parameter was defined. The change of the criterion function as the parameters were varied was observed.

A two-dimensional finite difference model of stress-sensitive geopressured - geothermal closed square reservoir saturated with a single-phase , slightly compressible fluid was used for the study. Single and two-parameter controlled experiments were performed on the initial formation permeability , porosity , uniaxial compaction coefficient , net pay thickness and the specific productivity index. The parametric calculations indicated that geopressured-geothermal reservoir pressure is sensitive to permeability, thickness, specific productivity index and uniaxial compaction coefficient, but porosity has little influence on calculated pressures.

RESUMEN

Este trabajo presenta los resultados de un estudio que investiga la susceptibilidad de la presión de un yacimiento a los parámetros esfuerzos. Yacimientos sensitivos a esfuerzos son aquellos cuyas rocas tienen propiedades que dependen de los esfuerzos efectivos sobre las mismas. El estudio de sensitividad a la presión fue hecho con experimentos controlados numéricamente, donde los parámetros de interés fueron variados uno a uno , o conjuntamente y el efecto de las variaciones sobre la presión de yacimiento fue observada. Una función criterio que caracteriza la diferencia entre las presiones calculadas usando cierto valor del parámetro y un valor de base supuesto para el parámetro fue definida. Se observó el cambio en la función criterio con la variación de los parámetros.

Un modelo bi-dimensional de diferencia finita de un yacimiento cuadrado, cerrado, geotérmico, geopresurizado, sensitivo a esfuerzo, saturado con un fluido ligeramente compresible en una sola fase fue usado para el estudio. Experimentos controlados con uno y dos parámetros fueron desarrollados sobre permeabilidad inicial de la formación, porosidad, coeficiente de compactación uni-axial, espesor, y el índice de productividad específico. Los cálculos paramétricos indicaron que el yacimiento geopresurizado - geotérmico es sensitivo a

la permeabilidad, espesor, índice de productividad específico y coeficiente de compactación uni-axial, pero la porosidad tiene poca influencia sobre las presiones calculadas.

INTRODUCTION

The effective stress on a reservoir rock is the difference between the overburden (confining) pressure and the pore pressure. The effective stress changes during a field operation. A reservoir whose rock properties change with variations in the effective stress is termed stress-sensitive. Reservoirs in compacting environments are in this category.

The sensitivity of reservoir performance data such as the pore pressure to pertinent reservoir parameters has been documented for reservoirs that are normally pressured and in non-compacting environment [2,3,14]. The relationship between the reservoir pore pressure or the overburden pressure and the reservoir parameters as well as the interrelationship of the reservoir parameters have been shown by various authors for reservoirs in both compacting and non-compacting media [7-10,13,15]. Relatively less work has been reported on the former reservoir system.

This study was made to investigate the sensitivity of reservoir performance data, specifically the bottom hole flowing pressure of stress - sensitive reservoirs to their pertinent parameters. The parameters investigated include the initial formation permeability, porosity and the sediment compressibilities (rock matrix compressibility and uniaxial compaction coefficient). The sensitivities were determined by performing numerically controlled experiments. A numerically controlled experiment consisted of several numerical reservoir simulation runs in which several values of a parameter, within a specified range about an assumed base value were used as input for the simulator. The differences in the temporal response of the calculations using the base parameter values and the perturbed parameter values were observed. The differences in the temporal response of the models showed the sensitivity of the performance data to the parameter varied. In a controlled experiment, the values of all reservoir parameters, except those being studied, were assumed known. The sensitivities were further investigated by observing the relationship between a defined criterion function and the initial parameter(s). The criterion function was defined (See Appendix) to characterize the difference between the performance data using the assumed parameter base values and the performance data using perturbed parameter values. Sensitivity from the criterion function is measured by the distinguishability obtained. The distinguishability reflects the change in the criterion function value for a small perturbation in the studied parameter [5]. High distinguishability would then imply high sensitivity and vice versa.

For this study, a hypothetical compacting geopressured-geothermal closed square reservoir was assumed. Geopressured-geothermal reservoirs are aquifers with higher pressure and temperature gradients than those normally encountered. As a result of their geology, formations that exhibit geopressured/geothermal behaviour are under-compacted and hence, stress-sensitive. Geopressured-geothermal formations have been found in many areas of the world including the United States Gulf Coast [1,4]. The reservoir mechanics of geopressured-geothermal reservoirs have been described [11,12]. A two-dimensional finite difference model of the reservoir was used for simulation. A single-well produced for 200 days from the center of the closed aquifer. The computer calculated well block pressures were converted to bottom hole flowing pressures [16]. The base data for the hypothetical reservoir are shown in Table 1. In the study, both single-parameter and two-parameter controlled experiments were performed on the parameters of interest. In the former case, only one parameter was varied during an experiment and its effect on the pressure behaviour was sought. In the latter case, two parameters were varied and their joint effects were sought.

The various parameters were controlled using the equation:

$$x_j = \hat{x}_j \pm a\hat{x}_j$$

where

x_j = value of the j^{th} parameter used in the simulator

$\hat{x}_j$ = base value of the j^{th} parameter

a = fractional number $(0 \leqslant a \leqslant 1)$

The results of the parametric calculations are discussed in the following section.

RESULTS

The results of the controlled experiments are presented in two subsections. One subsection describes the results of the single-parameter experiments while the other subsection describes the results of the two-parameter experiments.

SINGLE-PARAMETER EXPERIMENTS

In single-parameter experiments, the sensitivity of pressure to each of the pertinent parameters was determined. The result of each experiment is analyzed as follows:

Initial Permeability Experiment: The initial permeability values used ranged from *16 md* to *24 md* with a step size of *2 md*, which is *0.1* of the *20 md* base value. Figure 1 shows the temporal decline of the bottom hole flowing pressure for the selected permeability values. It can be seen that the temporal response is sensitive to the initial formation permeability. Permeability values higher than the base value resulted in significant higher pressure levels while lower permeabilities resulted in lower pressure levels. This is reasonable since to maintain a constant rate, a high permeability reservoir would require low potential gradients within the reservoir and vice-versa. Shown in Figure 2 is the plot of the criterion function versus the permeabilities. A convex surface was obtained with the minimum occuring at the base value as expected. The sensitivity of pressure to the permeability can also be seen in Figure 2 as the distinguishability is high. Notice that the criterion function value increases more rapidly below the base permeability than above it. In other experiments not reported in this paper, it was found that the pressure sensitivity was greater at low base permeabilities than at high base permeabilities.

Uniaxial Compaction Coefficient Experiment: Compaction coefficient is a measure of the deformation in an elastic porous media; the deformation is a result of the effective stress. Compaction coefficient is a function of the reservoir's pressure, temperature and lithology. As shown in Figures 3 and 4, there was considerable sensitivity of the temporal response of pressure to changes in the compaction coefficient. However, the sensitivity is not as great as that for permeability. Notice the difference in vertical scales between Figures 2 and 4. As in the case of permeability, the bottom hole flowing pressure decline curves lie above or below the base curve for compaction coefficient values higher or lower than the base value respectively. The fashion of the curves' displacement, however, is not the same for both parameters after the system reached pseudo-steady state. In the permeability experiment (see Figure 1), the displacement between any pair of curves remained constant during pseudo-steady state while the displacement continues to increase in the compaction coefficient experiment (see Figure 3). This difference was caused by the fact that a closed system was modelled. After the transient flow period had ended, the reservoir pressure gradients necessary to maintain the required flow rate were established and the reservoir followed a volumetric depletion, that is, the pressure decline with time became constant. For variations in permeability, the required pressure gradient must be different, but if porosity and sediment compressibilities are held constant, the rate of volumetric depletion must be the same. Hence, the curves of Figure 1 are parallel after transient flow period. However, for variations in sediment compressibilities and a constant permeability, the required gradients are equal but the rate of pressure decline with time will vary according to the changes in storage capacity of the aquifer. The storage capacity of the aquifer is a function of the sediment compressibilities and not a function of the permeability. Figures 5 and 6 qualitatively show the sensitivities of pressure to permeability and compaction coefficient, respectively, at various times in closed square aquifers. The compaction coefficient was assumed constant over the drawdown period.

Initial Porosity Experiment: The initial porosity was varied from 10 percent to 30 percent about a base initial porosity of 20 percent. It can be seen from Figure 7 that there was virtually no difference between the temporal pressure responses throughout the range. This observation seems to be a distinguishing characteristic of compacting reservoirs. A test run made with only fluid compressibility and no sediment compressibilities resulted in high pressure sensitivity to porosity. The pressure insensitivity obtained in this experiment was deemed caused by the large sediment compressibility value (10.0 micro-sips) assumed for the hypothetical reservoir. A convex surface was generated for the criterion function-porosity plot. The porosity distinguishability was several orders of magnitude smaller than those obtained in the permeability and compaction coefficient experiments. Figure 8 shows the criterion function-porosity plot.

Initial Reservoir Thickness Experiment: The results of the controlled experiment on the reservoir's net pay thickness are presented in Figures 9 and 10. As can be inferred from the figures, the reservoir temporal response is very sensitive to the thickness. Notice the strong similarity between the permeability and reservoir thickness experiments response.

Initial Specific Productivity Index Experiment: The ratio of the production rate, in stock tank barrels per day, to the product of the reservoir pressure drawdown at half time step, $\frac{\Delta t}{2}$, and thickness is known as the specific productivity index [2]. The specific productivity index, J_s, can be obtained thus: Assume steady state fluid flow in the well block, that is, the mass of fluid entering the block equals the mass leaving it ; radial incompressible fluid flow and Darcy's law applicable. We would then have

$$q_w = \frac{\theta 2\pi k h \Delta P_b}{\mu B_w \, \ell n(r_b/r_w)}$$

where

θ = units conversion factor
ΔP_b = pressure drawdown in a well block
r_b = effective wellbore radius

Rearranging the above equation, we have

$$\frac{q_w}{h \Delta P_b} = J_s = \frac{\theta 2\pi k}{\mu B_w \, \ell n(r_b/r_w)}$$

In engineering (field) units, $\theta 2\pi = 141.2$ or

$$J_s = \frac{141.2\,k}{\mu B_w \, \ell n(r_b/r_w)}$$

Figures 11 and 12 show the results of the controlled experiment on the specific productivity index. The results and observations of the permeability and thickness experiments discussed above are applicable here.

Multi-Parameter Experiments

Three of the parameters discussed above, permeability, uniaxial compaction coefficient and porosity , were considered for the multiparameter experiments . Only two-parameter experiments were performed. That is, two of the parameters above were varied during an experiment while the third parameter was held constant. Hence, three multiparameter experiments were performed using the controlling equation given above. The joint effect of the parameters was determined by observing the contours of the criterion function and also the distinguishability along the parameters' axes. The experiments are discussed below.

Initial Permeability and Compaction Coefficient Experiment: Values of the criterion function for various combinations of permeability and uniaxial compaction coefficient are shown in Figure 13. Some contours of the criterion function are also shown in the figure. Notice the contour scale at the top of the figure. These results show that the pressure response is sensitive to joint variations in the parameters. The distinguishabilities are high. Distinguishabilities along the k-axis is greater than distinguishabilities along the C_m axis. This confirms the results of the single-parameter experiments on k and C_m.

Initial Permeability and Porosity Experiment: The distribution of the criterion function values and the contours of the functions, shown in Figure 14, confirm the great sensitivity of computed responses to permeability and low sensitivity to porosity. Notice the higher distinguishability in the low permeability region.

Initial Compaction Coefficient and Porosity Experiment : From the results of this experiment , shown in Figure 15 , it can be observed that the temporal response's sensitivity to porosity decreases along the increasing axis of the compaction coefficient. This is shown by the higher distinguishability at the low compaction coefficient level. Therefore, it can be concluded that by itself, porosity does not induce much sensitivity due to the effect of the compaction coefficient. The combination of uniaxial compaction coefficient and porosity yielded the lowest distinguishability of all the two-parameter controlled experiments and, correspondingly, the least sensitivity. If compaction coefficient and porosity are varied simultaneously according to a fixed relationship between the two parameters, the sensitivity of pressure response would be great.

DISCUSSION

Controlled experiments such as those performed in this study have many uses. One of these is a better understanding of the mechanics of the reservoir considered. Determination of reservoir parameters has always been of significant concern to the reservoir engineers. Consequently, several techniques have been developed for parameter determination. The most popular techniques are those of the conventional well test methods. Studies have shown that the conventional well test methods may not be suitable for estimating the initial values of stress-sensitive reservoir's parameters [7]. Elemo and Knapp [6], in their recent paper, confirmed the inapplicability of the conventional well test methods to stress-sensitive reservoirs and documented the degree of discrepancy that can be expected if the well test methods are applied. An alternative to the well test methods is the history matching technique whereby the desired parameters are obtained by finding the parameter values that best match a set of field observed data and simulated data. The success of any history matching depends much on whether the performance data being matched are sensitive to variations in the parameters being estimated. Controlled experiments, as a tool for determining sensitivity, serves a useful purpose for determining which parameters can be estimated. Low distinguishability implies low sensitivity and, hence, a less probability of being able to accurately estimate the parameters involved by history matching. Controlled experiments therefore, can be a useful tool for petroleum reservoir engineers and ground water hydrologists.

CONCLUSIONS AND RECOMMENDATIONS

The results of the parametric calculations performed and discussed above have shown that the temporal response of pressure in stress-sensitive and compacting media is highly sensitive to variations in the formation permeability. The sensitivity to permeability is indirectly related to sediment compressibility. The results also indicated high sensitivity to the net pay thickness, specific productivity index and considerable sensitivity to the sediment compressibilities. The temporal response, however, was found to be insensitive to the formation porosity. Sensitivity to porosity was also found to be indirectly related to the sediment compressibilities. From the results, it can also be concluded that stress-sensitive permeability, sediment compressibilities, thickness and the specific productivity index can be accurately estimated by the technique of history matching. However, porosity estimation may present a problem. Any estimation involving porosity should be carefully analyzed.

NOMENCLATURE

C_m = Uniaxial compaction coefficient, psi^{-1} (10^6 *microsips*)

E = Criterion function, *psi-psi-day*

h = Net pay thickness, *feet*

J_s = Specific productivity index, *STB/day-psi-feet*

k = Formation permeability, *md*

p = Reservoir pressure, *psi*

q = Flow rate, *barrels/day*

r_w = Wellbore radius, *feet*

t = Simulation time, *days*

$\underset{\sim}{x}$ = Vector of reservoir parameters

$\hat{\underset{\sim}{x}}$ = Base value of $\underset{\sim}{x}$

β = Formation volume factor, Res. *bbl/STB*

Δt = Reservoir simulator time step, *days*

ϕ = Formation porosity, *percent*

μ = Fluid viscosity, *cp*

ACKNOWLEDGEMENT

The financial support for this study, furnished by the United States Energy Research and Development Administration and The University of Texas at Austin Center for Energy Studies, is gratefully acknowledged by the authors.

TABLE 1 : RESERVOIR BASE DATA FOR A HYPOTHETICAL SYSTEM

Drainage Area = 16 square miles

Reservoir Initial Pressure = 11,000 psi

Reservoir Temperature = 325°F - constant

Flow Rate = 15,000 STB/day

Formation Permeability = 20.0 md

Formation Porosity = 0.20

Net pay Thickness = 250 feet

Fluid Compressibility = 4.1×10^{-6} psi^{-1}

Uniaxial Compaction Coefficient = 10.0×10^{-6} psi^{-1}

Rock Matrix Compressibility = 0.0

Fluid Viscosity = 0.1856 cp

Fluid Density = 59.401 Lbm/ft^3

Fluid Density (Standard Conditions) = 62.757 Lbm/ft^3

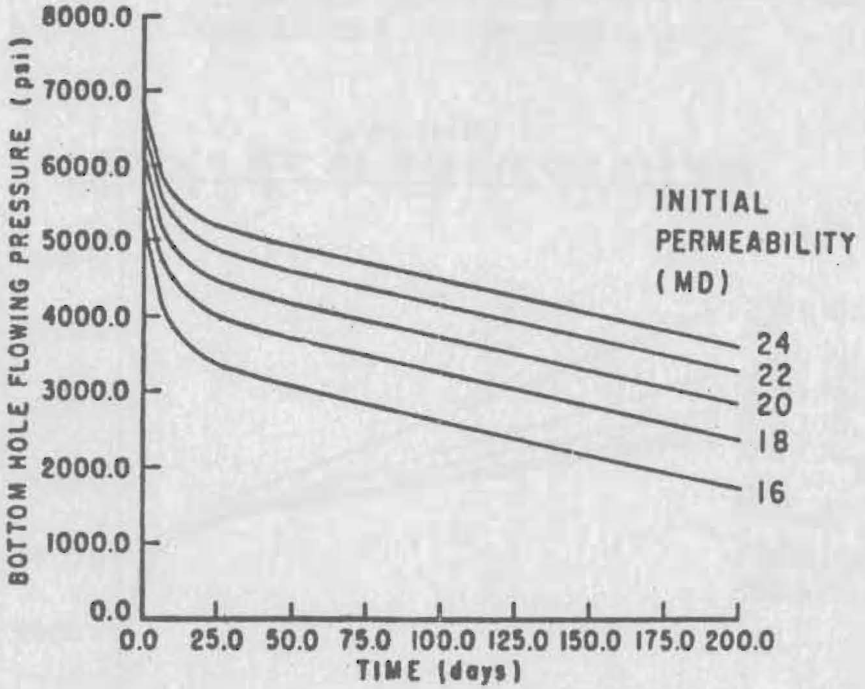

FIGURE 1: CONTROLLED EXPERIMENTS ON INITIAL PERMEABILITY

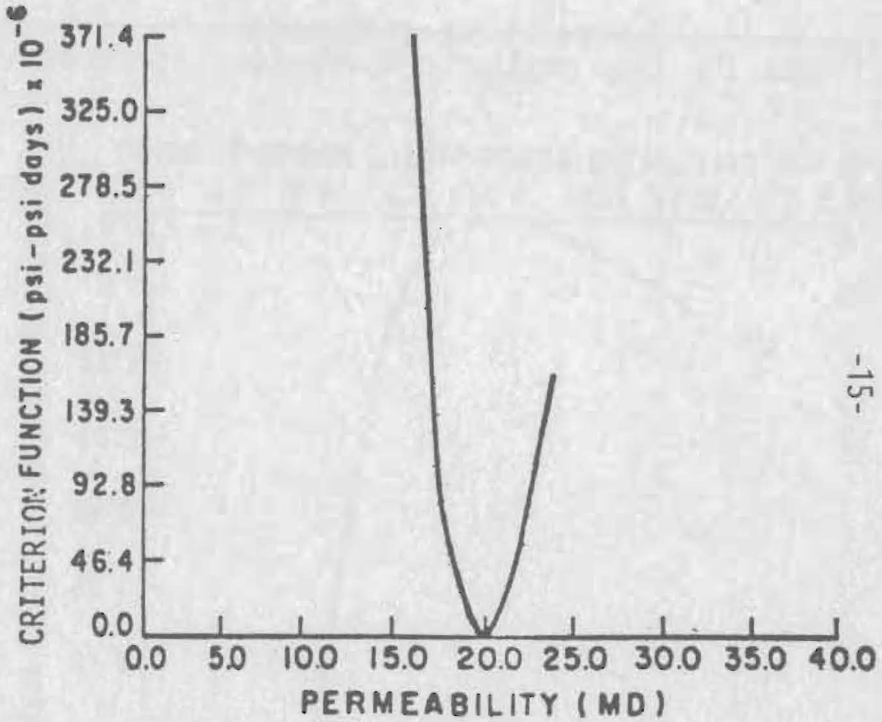

FIGURE 2: CRITERION FUNCTION VS. INITIAL PERMEABILITY FOR CONTROLLED EXPERIMENTS

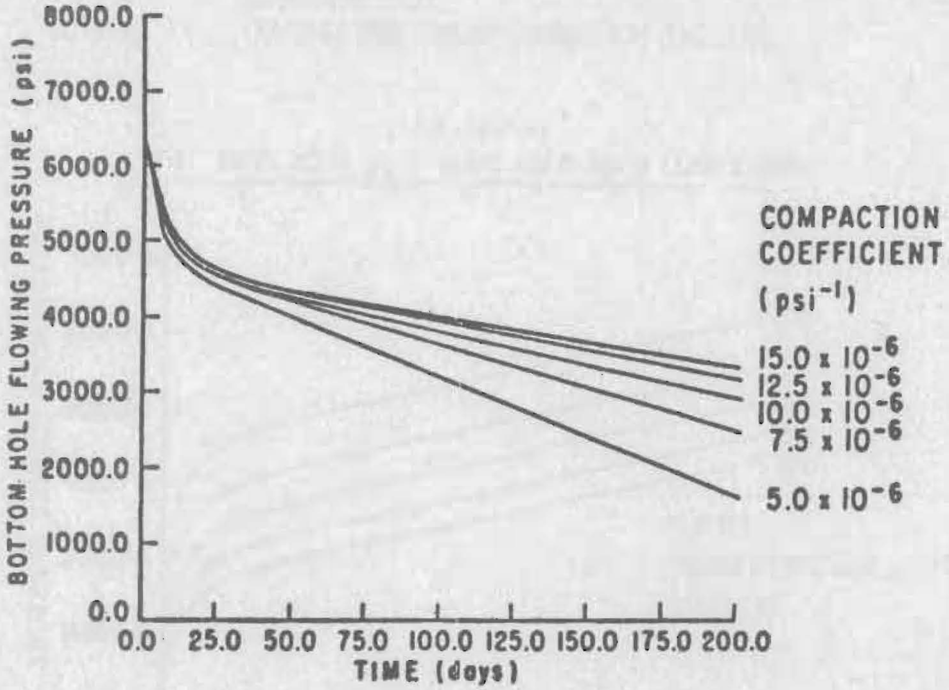

FIGURE 3: CONTROLLED EXPERIMENTS ON UNIAXIAL COMPACTION COEFFICIENT

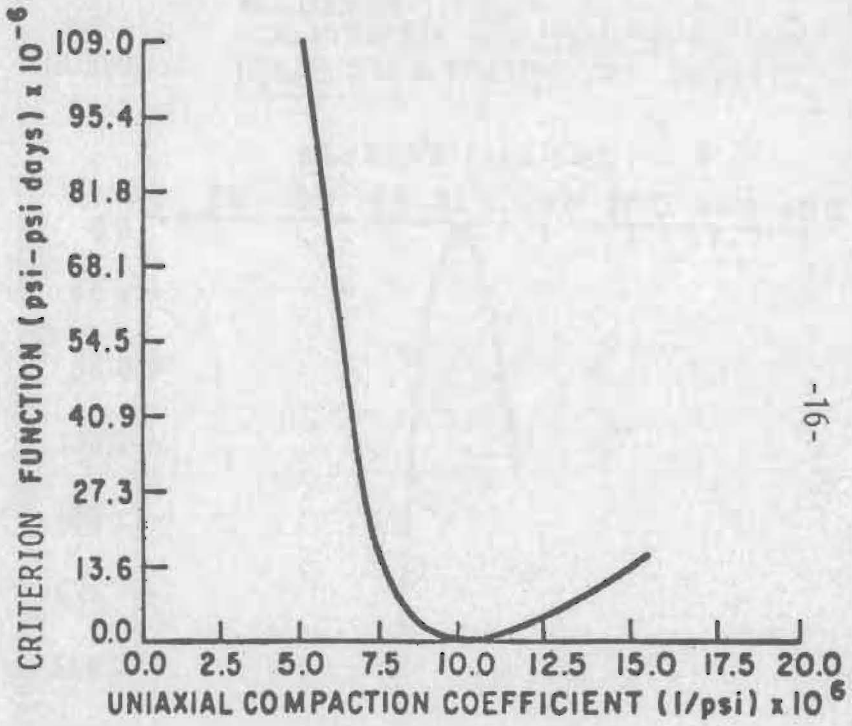

FIGURE 4: CRITERION FUNCTION VS. C_m FOR CONTROLLED EXPERIMENTS

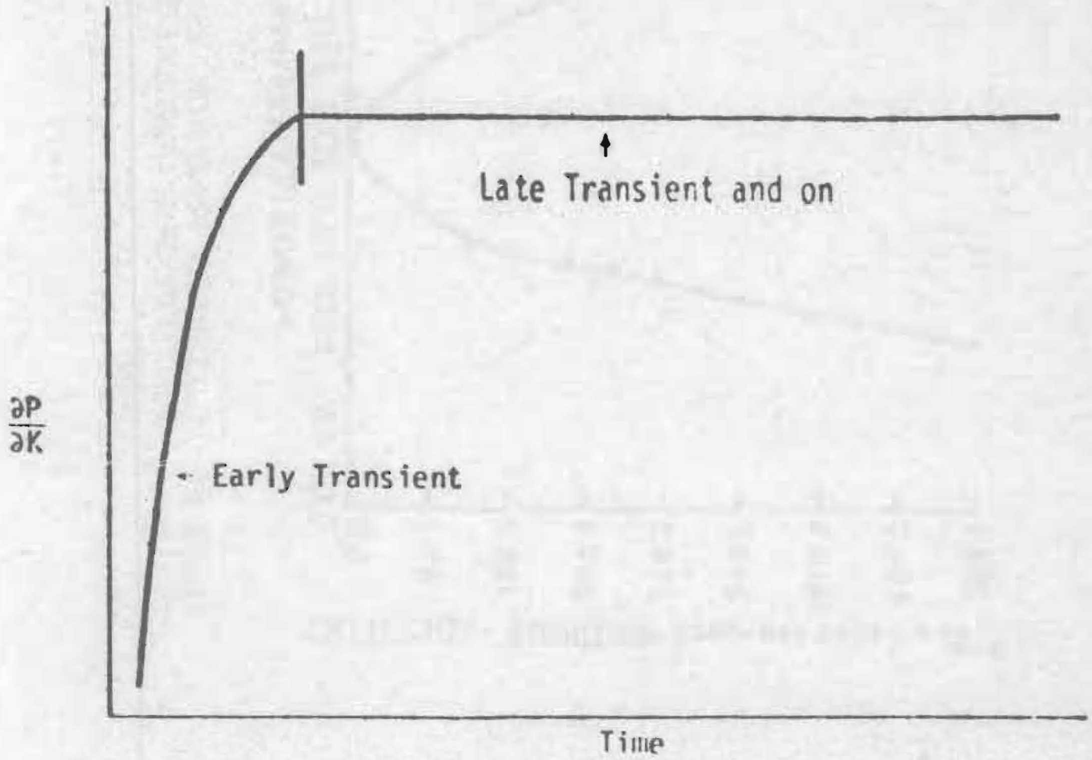

FIGURE 5: SENSITIVITY OF PRESSURE TO INITIAL PERMEABILITY AT VARIOUS TIMES FOR CLOSED SQUARE AQUIFER SYSTEMS

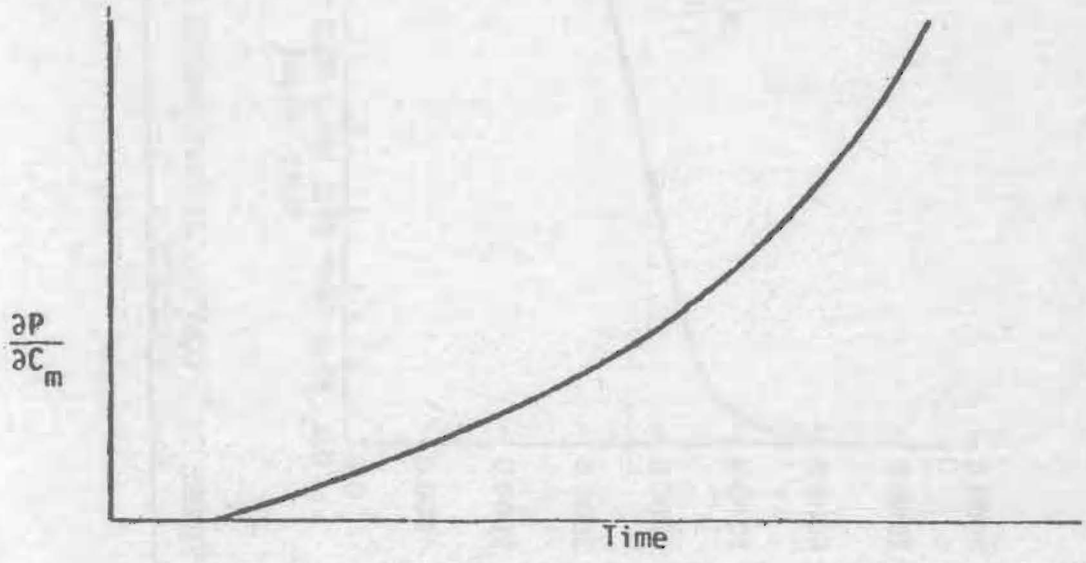

FIGURE 6: SENSITIVITY OF PRESSURE TO COMPACTION COEFFICIENT AT VARIOUS TIMES FOR CLOSED SQUARE AQUIFER SYSTEMS

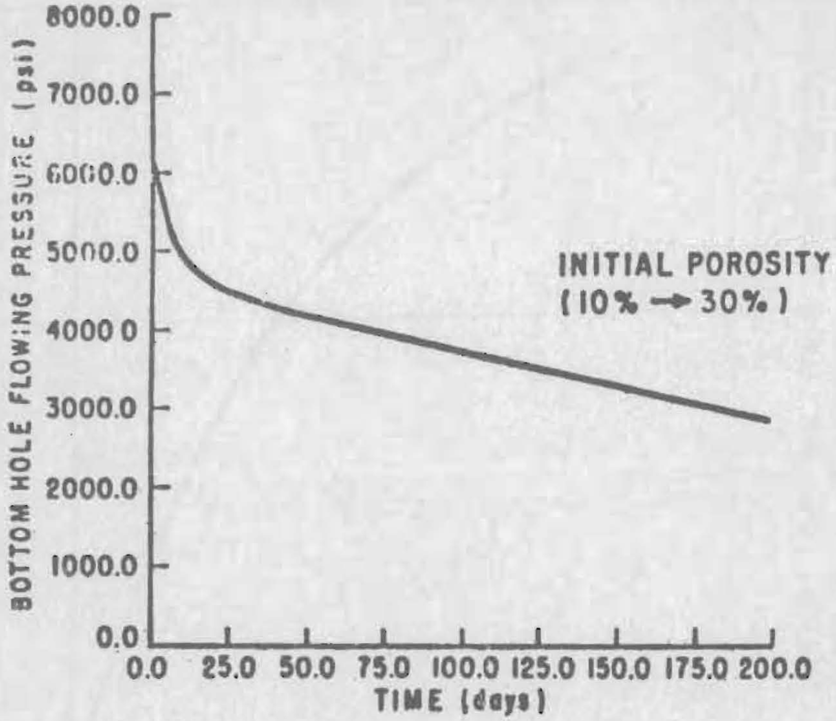

FIGURE 7: CONTROLLED EXPERIMENTS ON INITIAL POROSITY

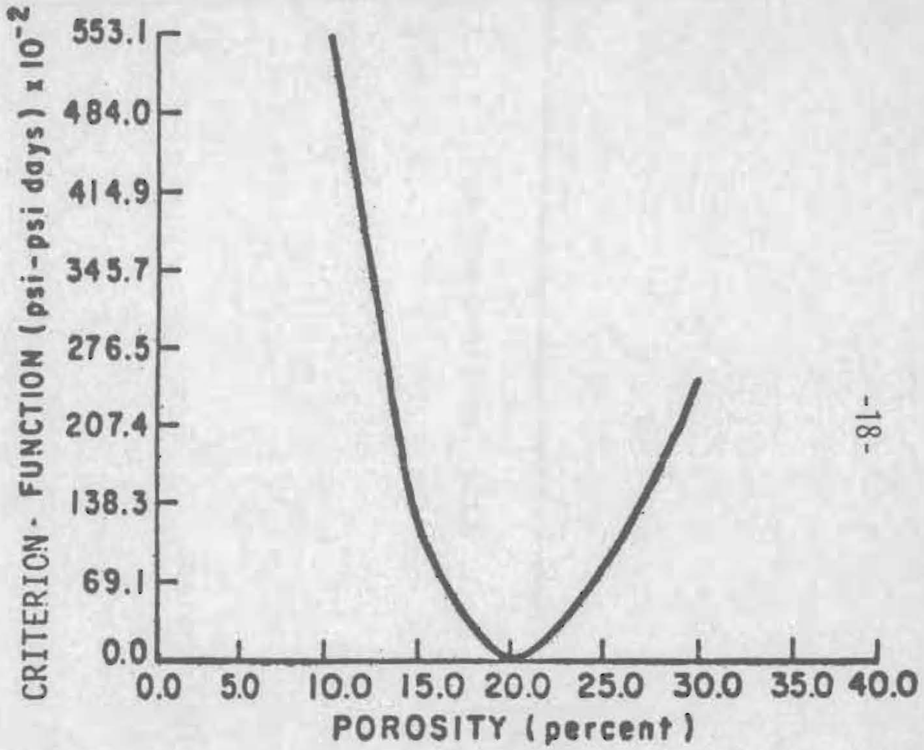

FIGURE 8: CRITERION FUNCTION VS. INITIAL POROSITY FOR CONTROLLED EXPERIMENTS

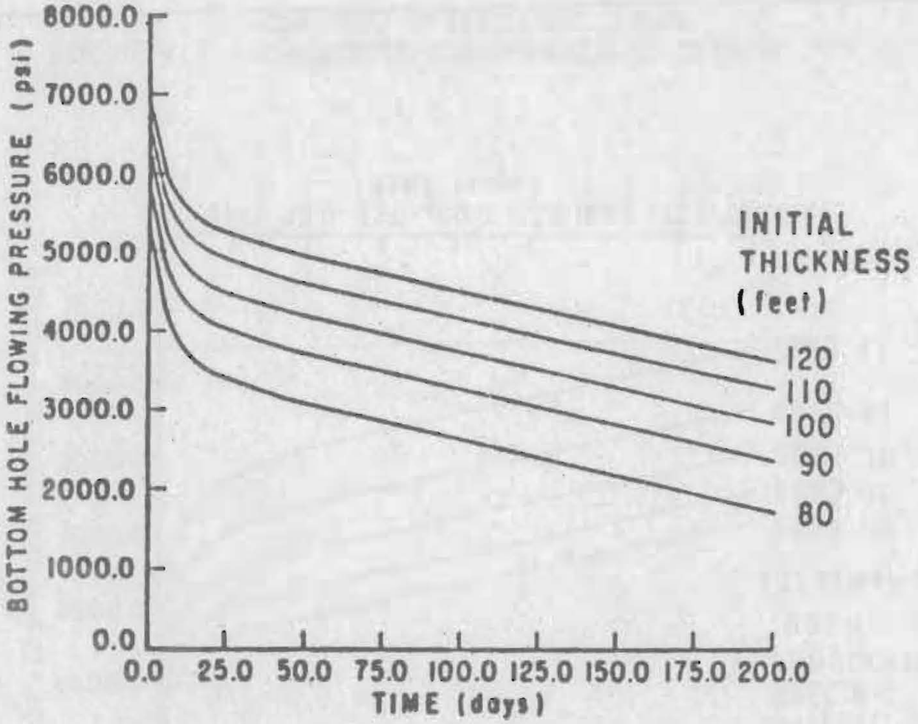

FIGURE 9: CONTROLLED EXPERIMENTS ON INITIAL RESERVOIR THICKNESS

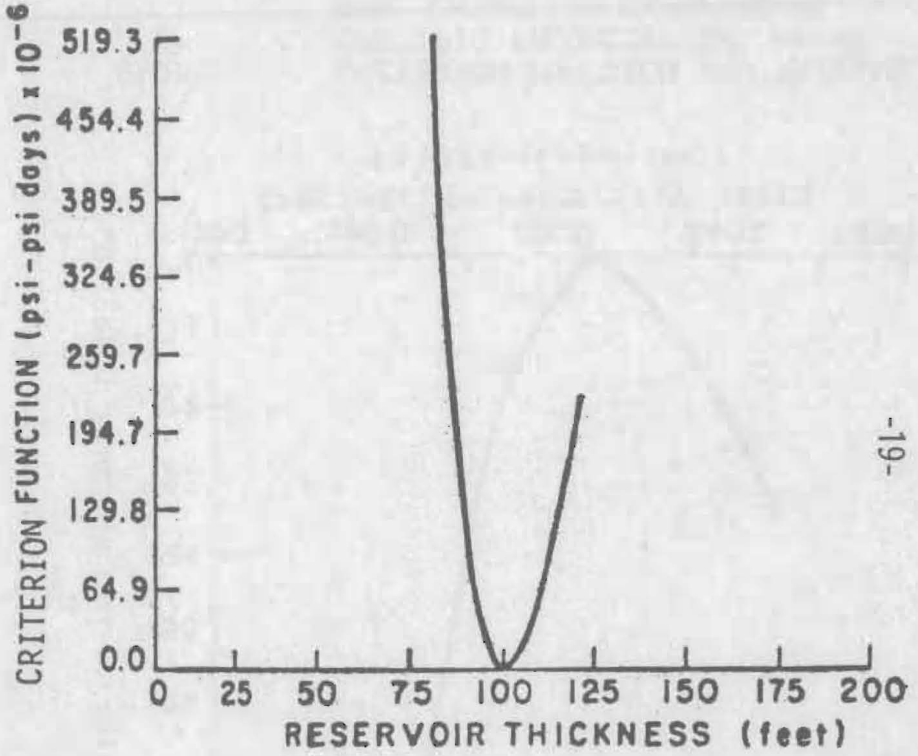

FIGURE 10: CRITERION FUNCTION VS. INITIAL RESERVOIR THICKNESS FOR CONTROLLED EXPERIMENTS

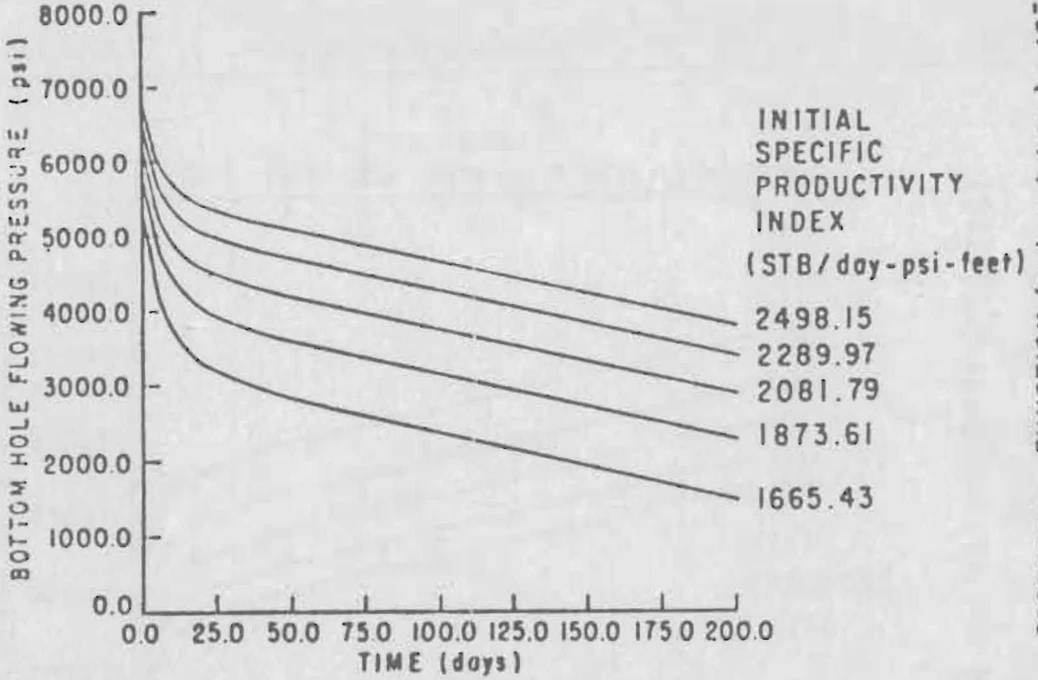

FIGURE 11: CONTROLLED EXPERIMENTS ON INITIAL SPECIFIC PRODUCTIVITY INDEX

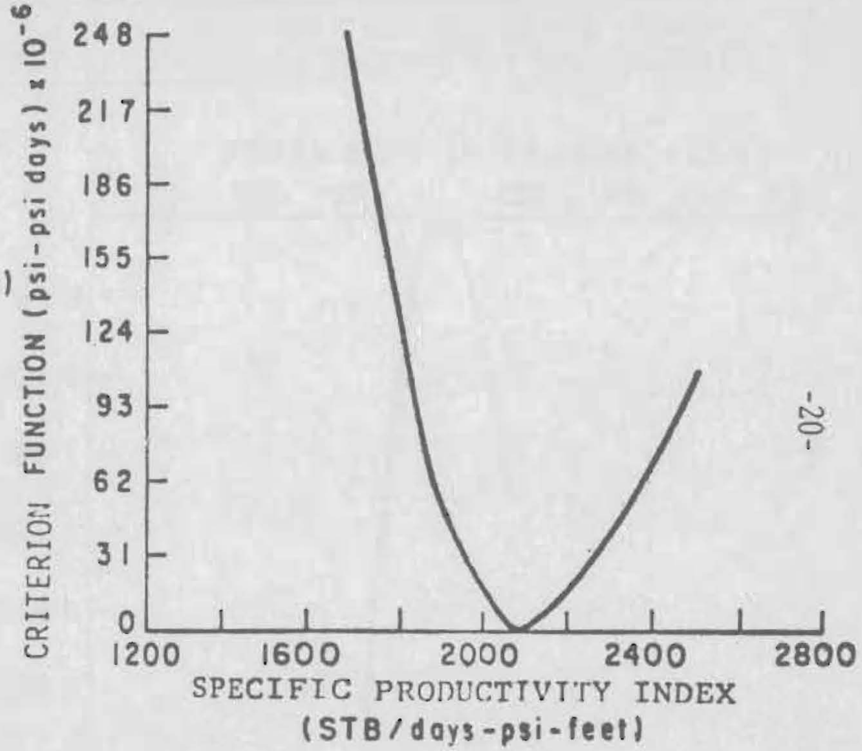

FIGURE 12: CRITERION FUNCTION VS. INITIAL SPECIFIC PRODUCTIVITY INDEX FOR CONTROLLED EXPERIMENTS

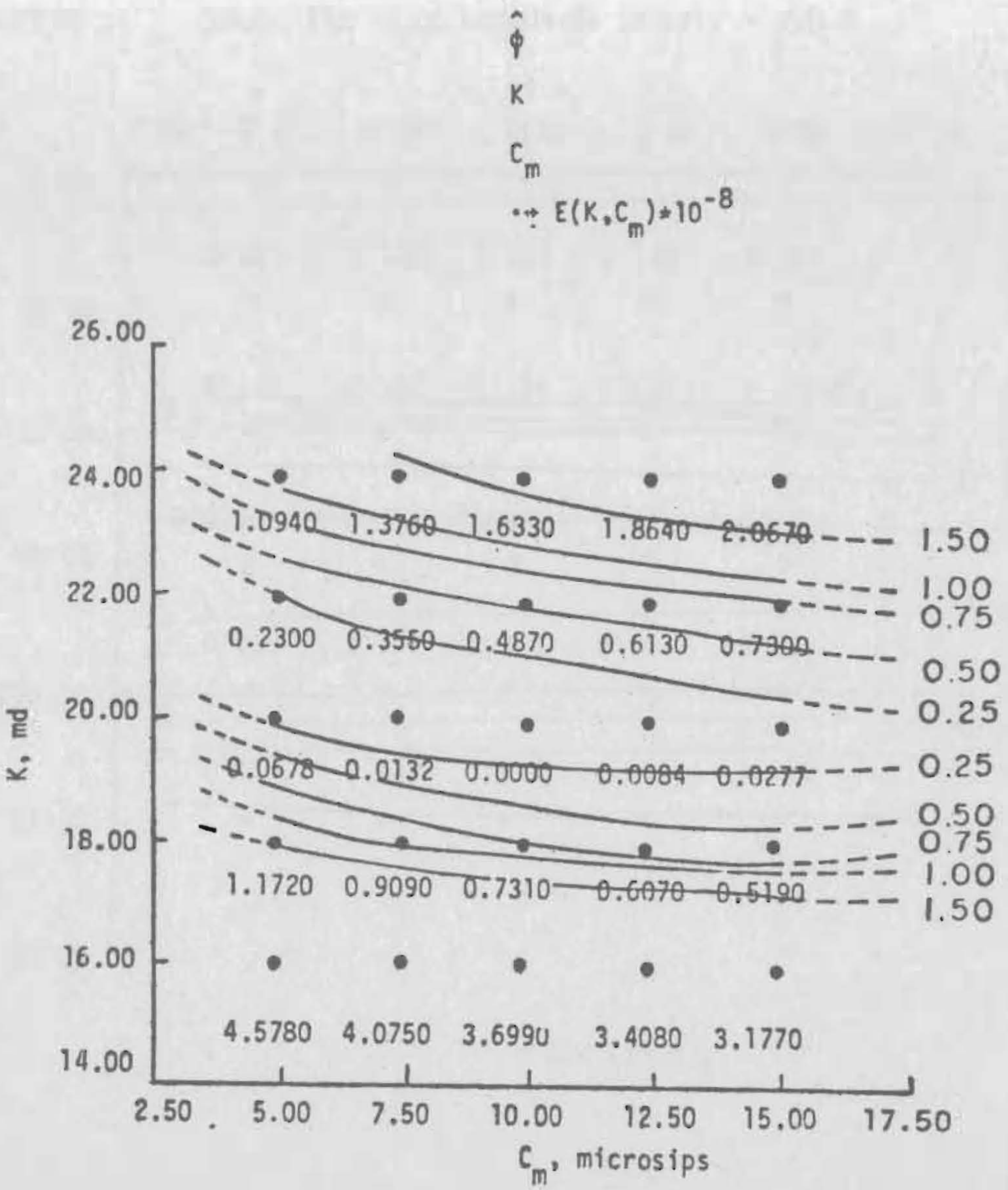

FIGURE 13: CONTROLLED EXPERIMENTS ON INITIAL *K* AND C_m

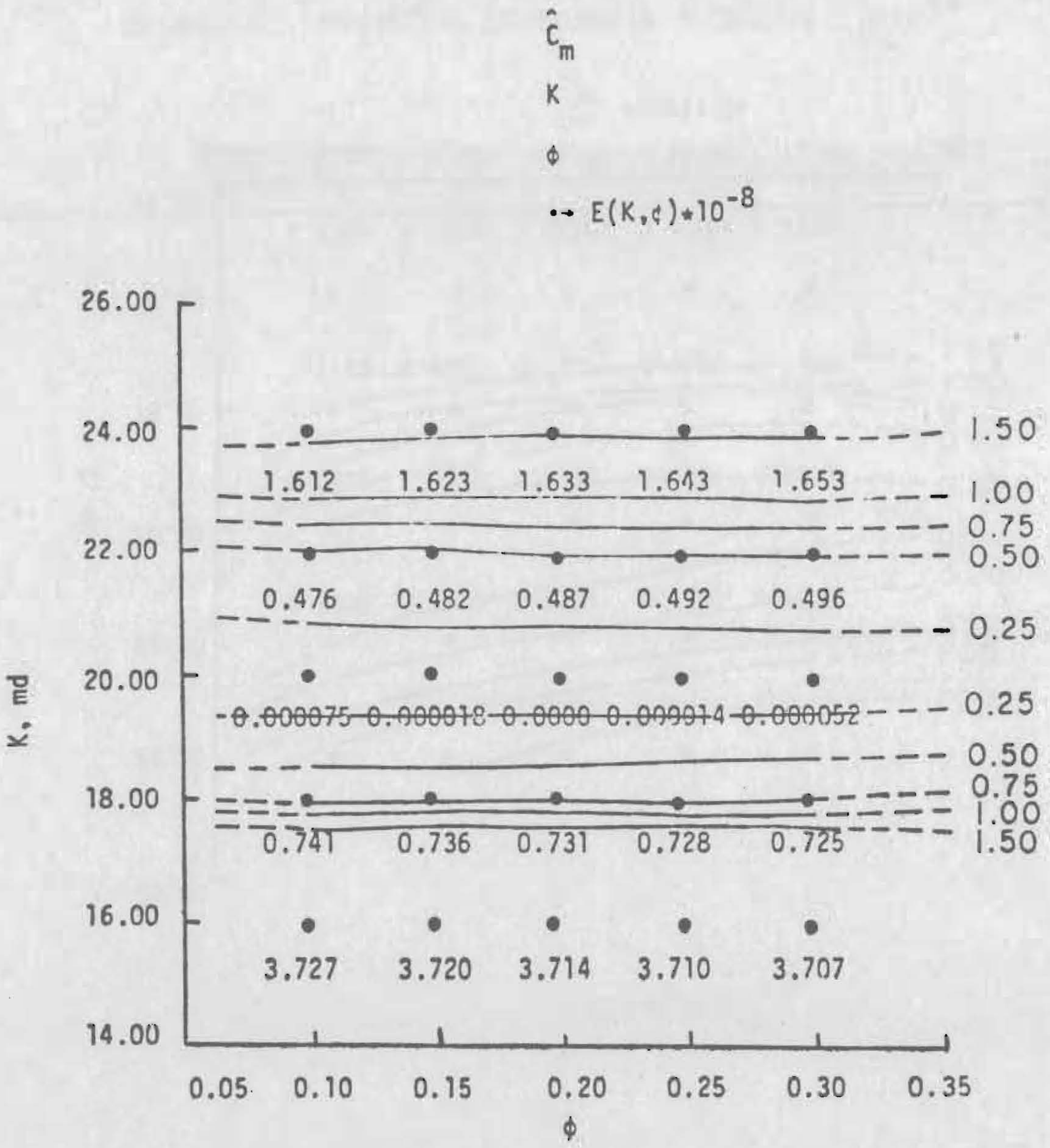

FIGURE 14: CONTROLLED EXPERIMENTS ON INITIAL *K* AND φ

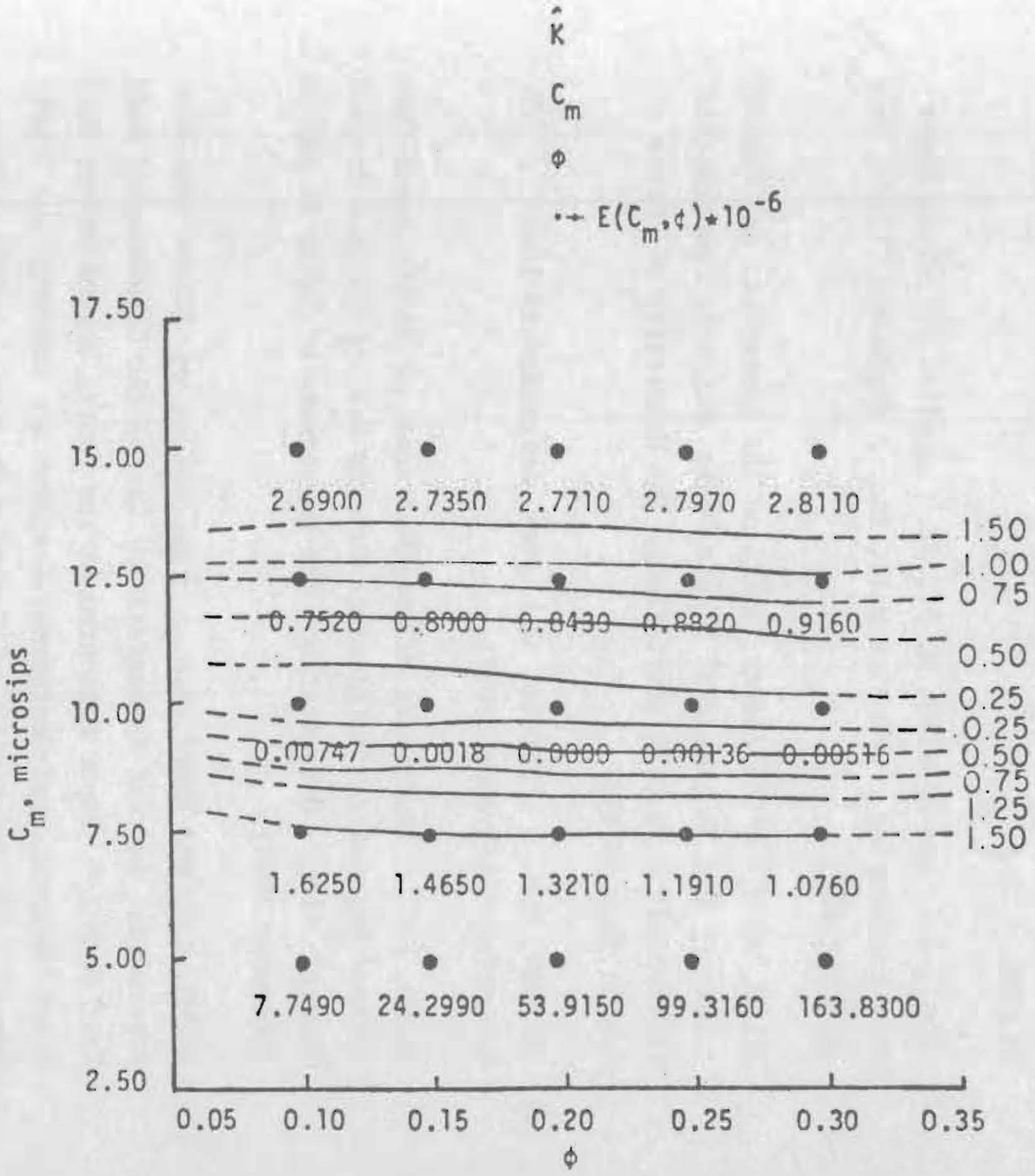

FIGURE 15: CONTROLLED EXPERIMENTS ON INITIAL C_m AND ϕ

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APPENDIX

Criterion Function

The criterion function is a mathematical formula that characterizes the difference between the temporal responses of a reservoir's performance data when some base parameter values and perturbed parameter values are used to run the reservoir simulator. The criterion function is a least squares criterion, that is,

$$E = \sum_{i=1}^{N} \sum_{k=1}^{M} \left(d_{i,k}^{b} - d_{i,k}^{p}\right)^{2}$$

where

$d_{i,k}^{b}$ = k^{th} performance data from i^{th} well obtained by running simulator with base parameter values, $\hat{\underset{\sim}{x}}$

$d_{i,k}^{p}$ = k^{th} performance data from i^{th} well obtained by running simulator with perturbed parameter values, $\hat{\underset{\sim}{x}} \pm a\hat{\underset{\sim}{x}}$

M = number of performance data simulated (number of time steps, $t/\Delta t$)

N = number of production/observation wells

The criterion function is a function of $\underset{\sim}{x}$; it becomes a functional if $\underset{\sim}{x}$ are functions of locations and/or boundaries of the reservoir.