Inflow Performance Relationships for Oil-Water Systems Above the Bubble Point

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ABSTRACT

This paper presents oil-water inflow performance relationships (IPR) for water drive reservoirs above the bubble point. A wide range of rock and fluid properties, relative permeability curves and initial water saturations has been considered. The effect of a skin region around the wellbore is also included in the analysis. The general theory and application of pressure-production relationships have been discussed.

INTRODUCTION

The production engineer often desires to predict the inflow performance of an individual well. The information is important for the following reasons:
1. Installation of production and artificial lift equipment.
2. Design and installation of surface facilities.
3. Profitability analysis of various operating scenarios.
4. Nodal systems analysis and optimization of the entire production system.
5. Planning and implementation of secondary recovery methods.

One of the earliest methods for predicting production rates is based on the concept of Productivity Index (PI) which is defined as follows:

$$J = q/(\bar{p} - p_{wf})$$

This straight line relationship can be derived from Darcy's law for the steady-state flow of a single, incompressible fluid. This concept is useful when the oil is undersaturated throughout the producing formation. One of the earliest investigations of oilwell performance for multiphase flow was conducted by Evinger and Muskat[1]. They concluded that for multiphase flow with a gas phase, one should not expect the PI to hold. Their theoretical calculations suggested that a curved relationship between production rate and pressure should be expected.

The purpose of the present study is to establish a relation between production and flowing bottomhole pressure for oil-water flow in a reservoir with a constant outer pressure boundary. An approximately linear relationship was observed between dimensionless pressure ($p_{wf}/\bar{p}$) and dimensionless flow rate (q/q_{max}) over the entire range of reservoir properties investigated.

The IPR for two-phase oil-water flow was practically identical to the IPR that would be expected for a single, homogeneous fluid flowing in the reservoir. The productivity index relationship could be used in order to predict pressure-production response for two-phase flow (oil and water) in a reservoir having a constant pressure outer boundary. Such a situation could occur if a reservoir is producing under the influence of a strong water drive or is undergoing waterflood operations.

DATA GENERATION

A finite difference reservoir simulator was used to model a single well radial flow system with a constant pressure outer boundary. For simplicity of analysis, a homogeneous system was considered for most of the cases. Reservoir parameters such as porosity and permeability were assumed to have the same value in all the grid blocks. However, the permeability near the wellbore was altered in several runs to simulate skin effects. The constant flow rate option of the model was used for all the runs. The oil properties were calculated using the correlation of Vazquez and Beggs.[2] The wetting and non-wetting phase relative permeability curves were determined by the method proposed by Brooks and Corey.[3] Water phase properties were obtained from Weinstein.[4]

RESULTS

The Productivity Index for single-phase flow of an incompressible fluid is defined as

$$J = \frac{q}{\bar{p} - p_{wf}} \quad \text{......} 1$$

If the PI is known, then the maximum production rate can be determined from

$$q\ max = J.\bar{p} \quad \text{......} 2$$

If we relate Eq 1. to Eq. 2, we can obtain an IPR for single-phase flow.

$$\frac{q}{q_{max}} = 1 - \frac{p_{wf}}{\bar{p}} \quad \text{.......... 3}$$

If we assume the PI concept holds good for both phases during two-phase, oil-water flow we might expect the following linear relationship to hold

$$\frac{q_j}{q_{j\,max}} = 1 - C_j \frac{p_{wf}}{\bar{p}} \quad \text{.......... 4}$$

where the subscript represents the phase. If Cj equals 1 then the single phase relationship is obtained.

For the cases studied in this research the value of Cj for the oil phase ranges from 1.013 to 1.094 and for the water phase from 1.043 to 1.200. This implies a linear relationship between $(p_{wf}/\bar{p})$ and q/q_{max}. The straight line was observed to hold for all the cases studied though its slope was different for each stage of depletion. In other words, the two-phase oil-water IPR is similar to an IPR for single-phase fluid flow in the reservoir. The above observations are evident from the two IPR curves presented later.

The effect of positive or negative skin near the wellbore has also been analyzed and the straight line productivity index concept seems to work equally well for these cases. Skin alters q as well as q_{max} to the same extent. The q/q_{max} ratio remains unaffected. Therefore the dimensionless form of the IPR remains unaffected by the presence of skin. This is evident from Figs. 9,10,11 and 12. This agrees with the work of Camacho and Raghavan[5] as well as Klins and Majcher[6] where they observed that the presence of skin has no effect on the IPR for two-phase, gas-oil, flow.

Figs. 1,2,4 and 5 show the dimensionless normalized curves for data sets 1 and 2 . The values of Cj (Eq 4) for oil are 1.050 and 1.056 while those for water are 1.047 and 1.044. Figs.7 and 8 show the dimensionless normalized curves for all the different reservoirs studied. The plots of oil production rate as a function of pressure drop($\bar{p}-p_{wf}$) can be see in Figs. 3 and 6. A straight line does reasonably well in matching the simulator results and indicates that use of the PI relation will yield suitable engineering accuracy. In order to use the PI relation one needs to record the average reservoir pressure, the flow rate and the flowing bottomhole pressure at a given value of Np/N. The only unknown in the PI equation is q_{max}, which can be calculated using the other variables. Once q_{max} is known, the PI relation can be used to predict production rates at different flowing bottomhole pressures.

CONCLUSIONS

In summary, dimensionless IPR curves were calculated for a number of theoretical water drive reservoirs at different stages of depletion. These reservoirs encompassed a wide range of reservoir data, fluid properties and relative permeability characteristics. The results suggest a linear relationship exists between q/q_{max} and $p_{wf}/\overline{p}$ for oil and water for all the cases studied. The PI relationship can be used to predict the pressure-production response for two-phase oil-water flow in a reservoir having a constant pressure outer boundary.

NOMENCLATURE

J	=	Productivity Index STB/day/psi
Np	=	Cumulative Oil Production STB
N	=	Oil in Place STB
P_{wf}	=	Flowing Bottomhole Pressure psi
$\overline{p}$	=	Average Reservoir Pressure psi
q_o	=	Oil flow Rate STB/day
$q_{o,max}$	=	Oil flow Rate at $P_{wf}=0$ STB/day
q_w	=	Water flow Rate STB/day
$q_{w,max}$	=	Water flow Rate at $P_{wf}=0$ STB/day

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2. Vasquez, M. and Beggs, H.D.: "Correlations for Fluid Physical Property Prediction," *JPT* (June 1980) 968-70.
3.Brooks, R.H. and Corey, A.T.: *Journal of Irrigation and Drainage Division*, ASCE, (June 1966) p61
4. Weinstein, H.G. *et al.*: "Second Comparative Solution Project: A Three Phase Coning Study," *JPT* (March 1986) 345-353.
5. Camacho, R.G. and Raghavan, R.: "Inflow Performance Relationships for Solution-Gas Drive Reservoirs," *JPT* (May 1989) 541-
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Table 1
Reservoir Properties Used In Simulation

	SET-1	SET-2
Drainage radius ft	847.26	361 .01
Porosity fraction	0.25	0.25
Permeability md	100	50
Well Radius ft	0.25	0.25
Initial pressure psi	2450	3500
Initial water saturation	0.3	0.2
Initial oil viscosity cp	2.12	3.1
Thickness ft	20.0	15.0

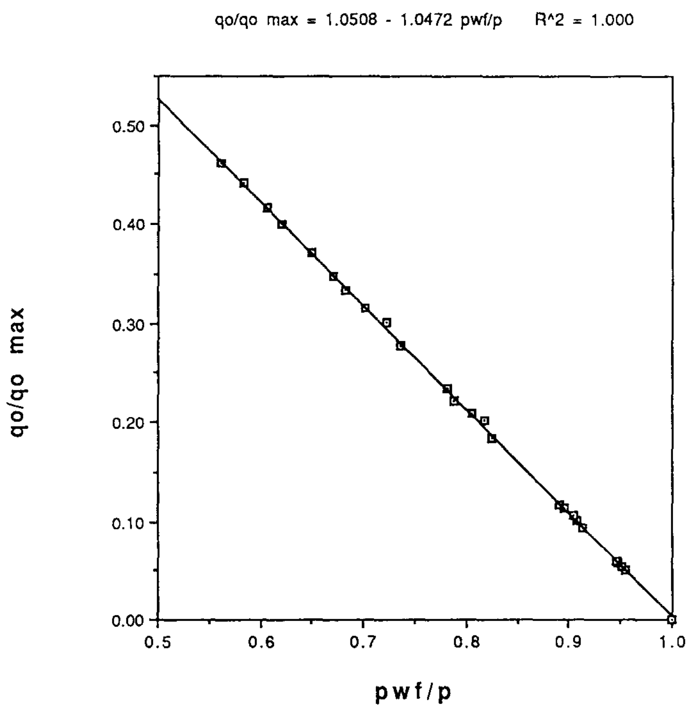

Figure 1 - Dimensionless oil IPR curve for set-1

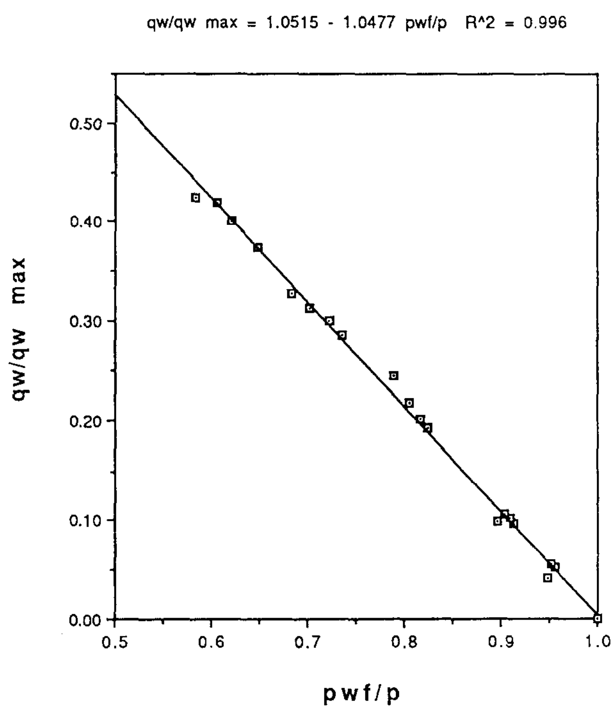

Figure 2 - Dimensionless water IPR curve for set-1

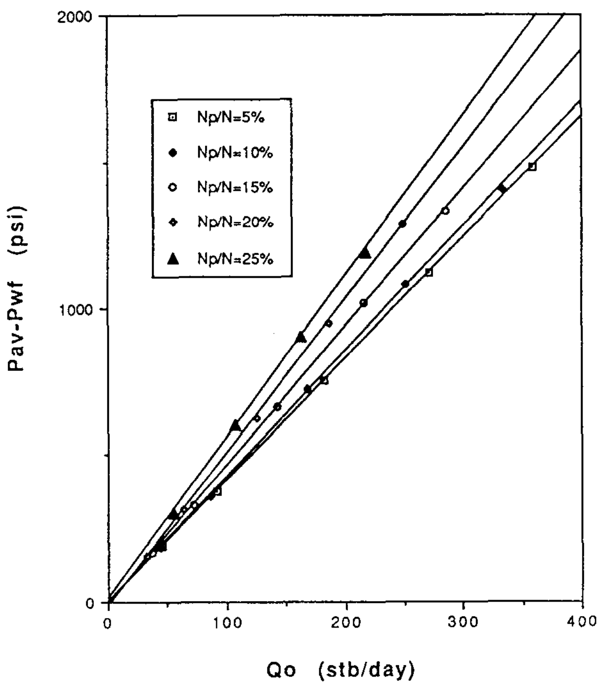

Figure 3 - Plot of oil production rate as a function of drawdown

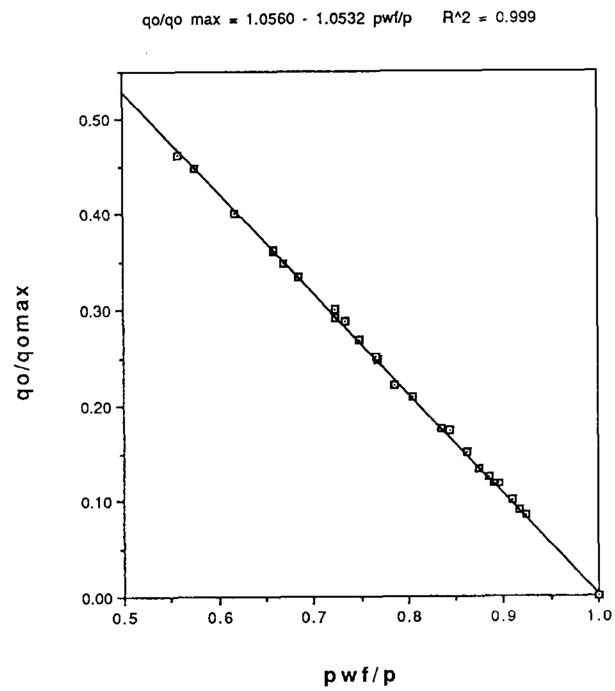

Figure 4 - Dimensionless oil IPR curve for set-2

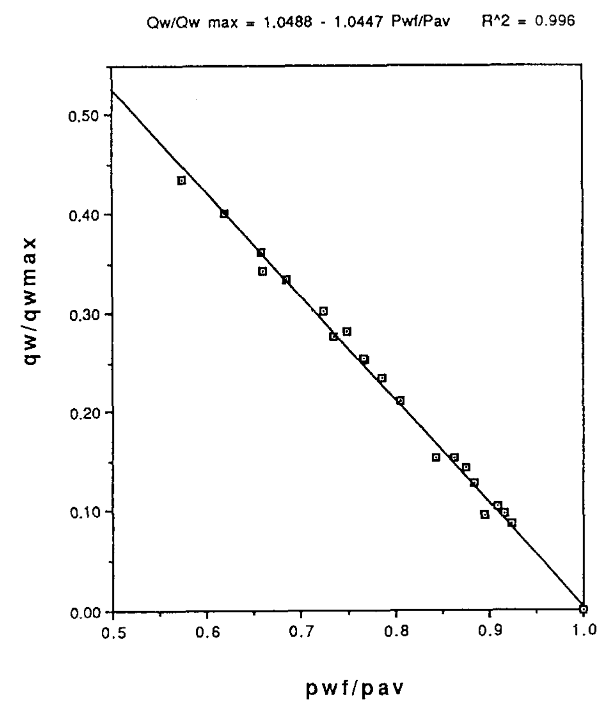

Figure 5 - Dimensionless water IPR curve for set-2

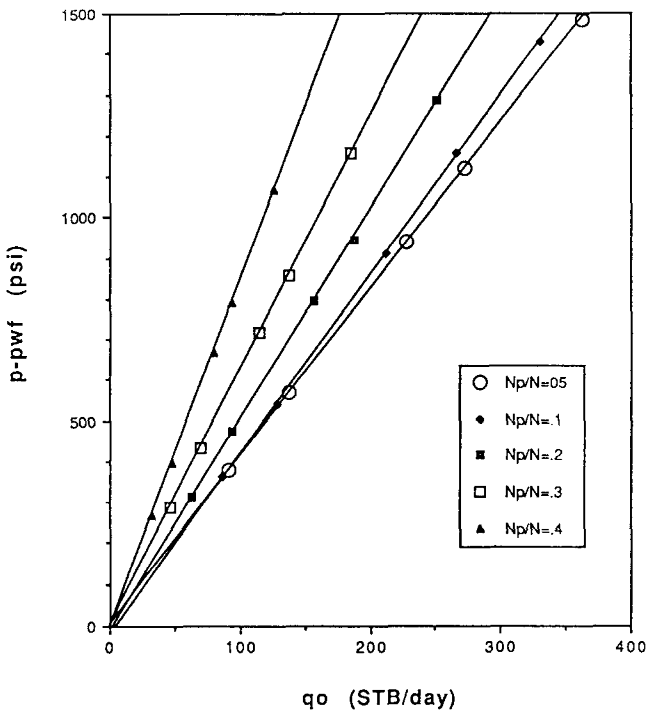

Figure 6 - Plot of oil production rate as a function of drawdown

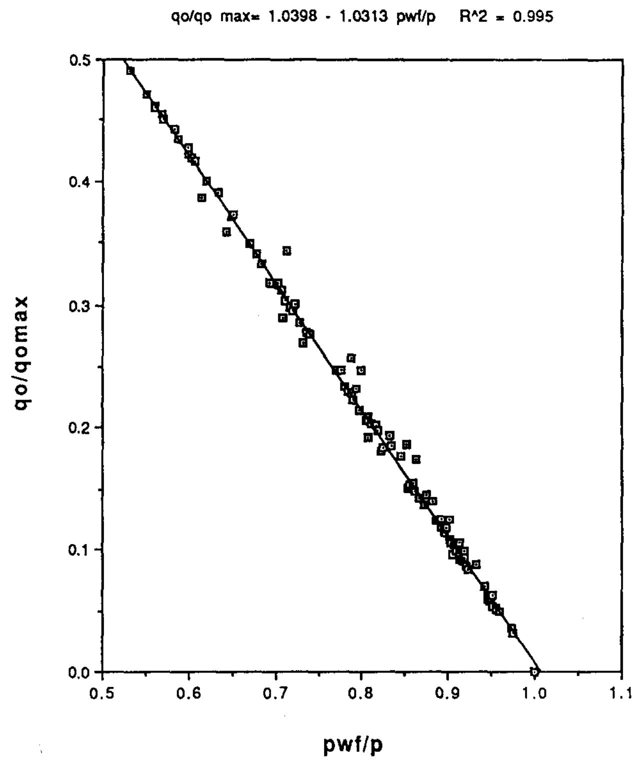

Figure 7 - Dimensionless oil IPR curve for all cases

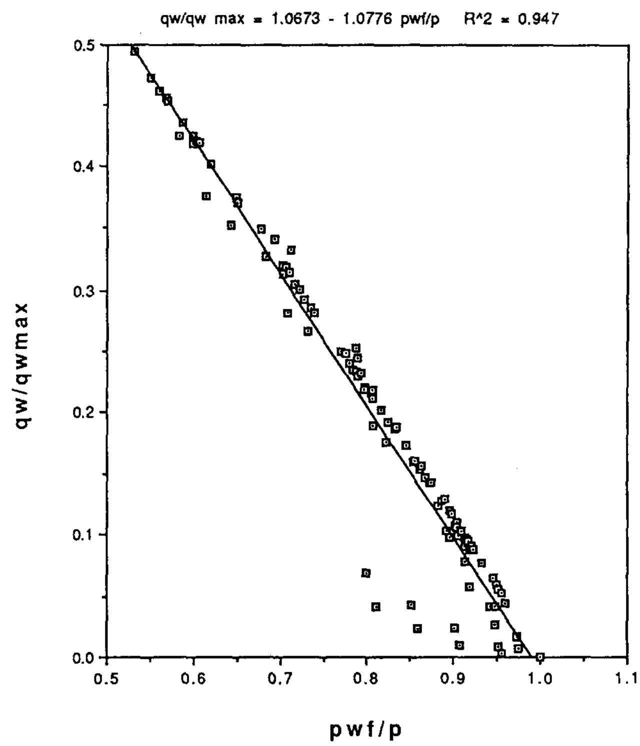

Figure 8 - Dimensionless water IPR curve for all cases

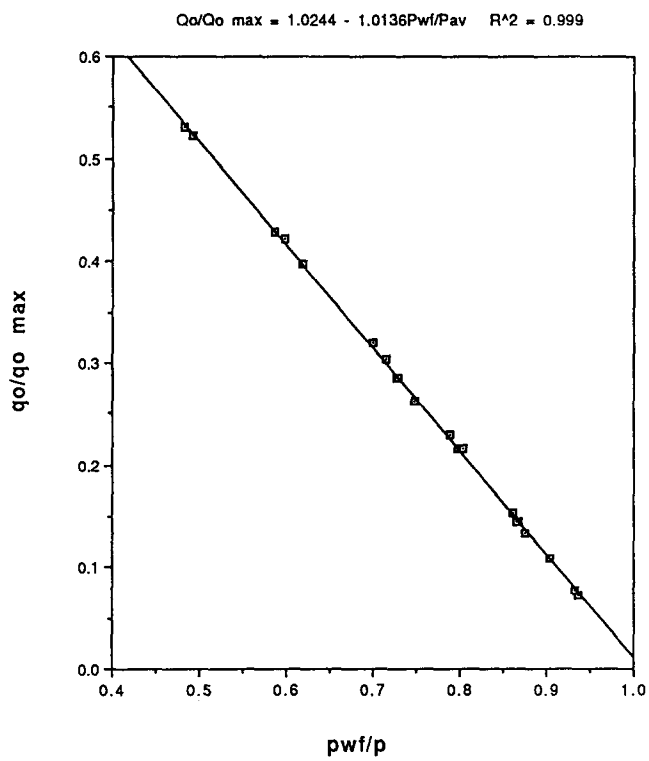

Figure 9 - Dimensionless oil IPR curve for case with skin = +3

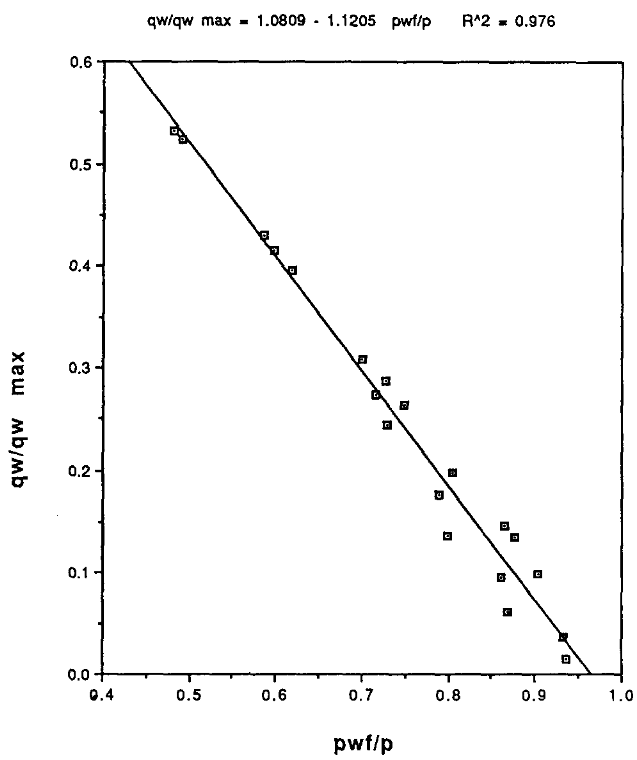

Figure 10 - Dimensionless water IPR curve for case with S = +3

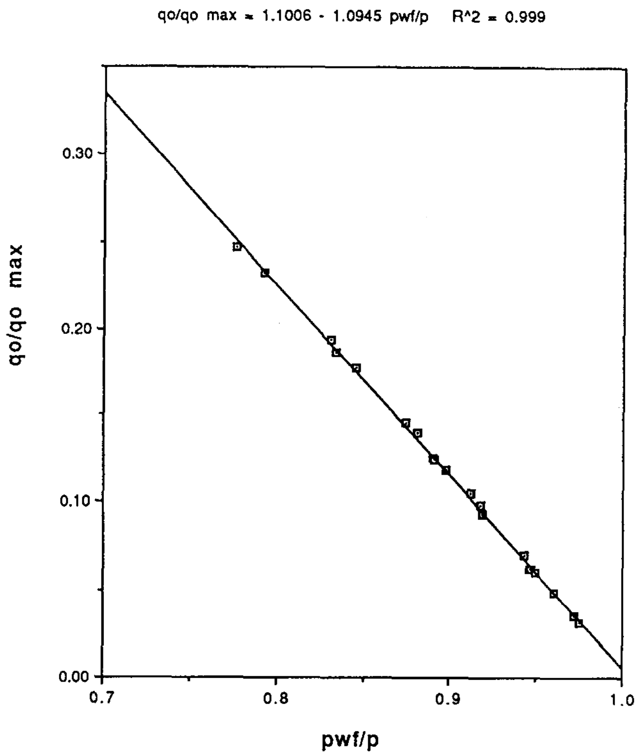

Figure 11 - Dimensionless oil IPR curve for case with S = -3

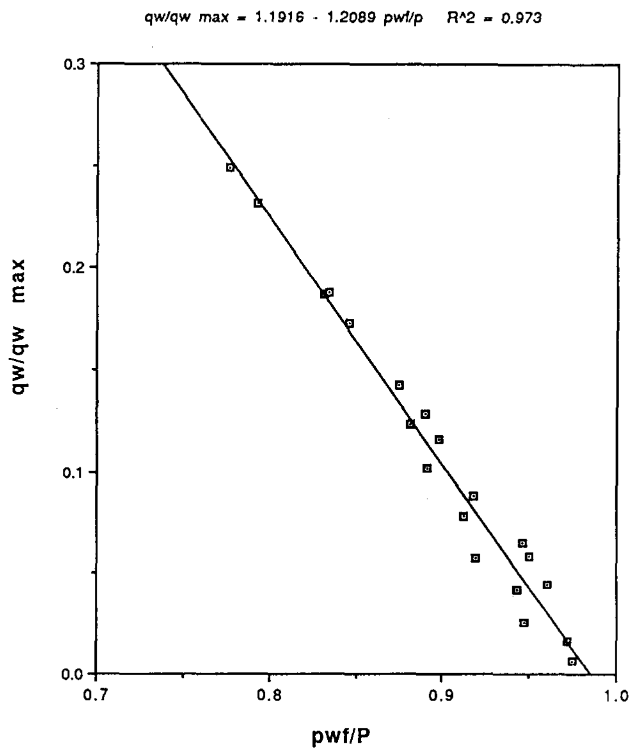

Figure 12 - Dimensionless water IPR curve for case with S = -3