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Field Applications of a Productivity Tool for Improved Oil Recovery (IOR)

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تطبيقات حقلية لأداء الإنتاجية لتحسين المسترد النفطي

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أظهرت الصناعة النفطية في الآونة الأخيرة زيادة في الوعي نحو المحافظة على إنتاجية أفضل للبئر من خلال تصميم أفضل لسوائل الحفر والاستكمال عند ضغط عال ودرجة حرارة عالية. وعلاوة على ذلك فإن آلية ترشيح سوائل الحفر وتأثيرها على آداء الإنتاج غير مفهوم عند ظروف قاع البئر.

وعند الانتهاء من البئر فإن فواقد الإنتاج حرجة لأن التلف الذي يحدث قرب فتحة البئر لا يمكن تخطيه بواسطة التثقيب، كذلك فإن أي نموذج مقبول لتطبيقات حقلية تحاكي الضرر قرب فتحة البئر من حيث أداء انسياب البئر المأخوذ من تحاليل لب البئر المعملية لا تتوفر حاليا.

تزود نتائج معطيات تجريبية معمقة مصحوبة بتحاليل بيانات نماذج ترشيح ساكنة ومتحركة قاعدة بيانات لنماذج آلية شبه تجريبية تم تطويرها.

تم ضم هذه النماذج ودمجها نحو أدوات تصميم وتقويم وأداة الإنتاجية وذلك للتنبؤ بتأثير ترشيح سائل الحفر ذو الضغط العالي ودرجة الحرارة العالية على إنتاجية التكوين من حيث ضرر التكوين بالآبار العمودية.

نقدم في هذه الورقة تطبيقات أداة الإنتاج باستخدام بيانات حقلية من حقول نفط بشمال أفريقيا (WBM and OBM)، تم اختيار السوائل لأنها تتناسب مع الضغط العالي ودرجة الحرارة العالية. وتظهر أداة الإنتاج توافقا جيدا مع القياسات الحقلية.

Abstract: *In recent times, the oil industry has shown increasing awareness towards maintaining optimum well productivity through better high pressure, high temperature (HP-HT) drilling/completion fluids design. However, the mechanisms of drilling fluid filtration and impact on productivity performance are not well understood under downhole conditions.*

In open hole completions, the productivity losses are critical because the near-wellbore damage is not by-passed by perforations. Furthermore, a satisfactory model for field applications to simulate the near-wellbore damage in terms of well flow performance from laboratory core test analysis still is not available.

The results of in-depth experimental data combined with data analysis of static and dynamic filtration models provides the database for the semi-empirical mechanistic models that were developed. These models have been combined and incorporated into a design and evaluation tool - the productivity tool (PRT), for predicting the effect of HP-HT drilling fluid filtration on formation productivity in terms of formation damage in vertical wells.

In this paper, we present applications of the PRT using field data from North African oilfields with both water-based and oil-based muds (WBM

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and OBM), both selected as suitable for HP-HT wells. The PRT shows good agreement with the field measurements.

INTRODUCTION

The most common source of formation damage has proved to be drilling operations[1]. Permeability is a characteristic of the formation, and can be altered by solids and mud filtrate invasion during drilling operations. Drilling fluids are used to facilitate various drilling processes. Drilling mud filtrate will invade the formation to a greater depth than drilling mud particles. A decrease of the permeability (formation damage), results in a decrease of the well productivity[2,3]. The formation damage depends upon many parameters such as formation characteristics, type, composition, filtration and rheological characteristics of drilling fluid and operating conditions (overbalance pressure, time, *etc.*).

A key parameter in quantifying formation damage is the skin factor[4]. The skin factor estimated from well test data is used in the inflow equations to estimate the production rate in wells that are affected by formation damage.

Generally, when rating performance of various drill-in fluid formulations, the permeability damage evaluation is quantified through oil return permeability measurements and flow-initiation pressures performed on core samples damaged during mud filtration tests[5,6].

Extensive laboratory studies of formation damage and several modeling efforts for prediction of formation damage have been reported in the literature. Most of the previous studies have focused on formation damage from drilling fluid filtration of water-based mud (WBM) and incompressible fluids in low-pressure, low temperature (LP-LT) applications.

Few attempts have been made to transfer these laboratory data into a near-wellbore model to evaluate the permeability damage. Liu *et al.*[7] simulated formation damage by fluid injection and mud filtration while Scott Lane[8] and Semmelbeck, *et al.*[9] simulated filtrate invasion for improving log interpretation, but their impact on well performance was not investigated. Some workers[10,11] studied well performance using representative formation damage, but laboratory tests were not integrated in their studies.

The economic impacts of wellbore formation damage justify a thorough study of this problem in order to find ways to minimize its effect on well performance.

This paper presents applications of the productivity tool using field data for screening different HP-HT drilling fluids (WBM and OBM), which specify the invaded zone skin as well as the depth of invasion, and evaluates the damage factor of a given fluid in terms of inflow performance.

FUNCTION OF THE PRODUCTIVITY TOOL

The productivity tool was constructed to provide a design and analysis package, which can be used to perform the following key functions:

1. To analyze wellbore pressure distribution.
2. To analyze the response of the fluid to static and dynamic filtration in an HP-HT environment.
3. To characterize the rheology and filtration of the selected fluids in an HP-HT environment.
4. Quantify the level and depth of damage and determine the best operating conditions.
5. Determine the impact of the selected fluid on formation productivity.
6. Screen appropriate HP-HT fluids desired for achieving minimum formation impairment.

In order to perform these functions, the productivity tool incorporates a number of mechanistic models, which have been developed as part of the initial project study, which include:

- Rheology prediction models.
- Static and dynamic filtration prediction models.
- Filter cake build-up on sand face evaluation models.
- Prediction models for filtration pressure drop across sand face and filter cake.
- Formation morphological characteristics.
- Prediction models for depth of solids and filtrate invasion.
- Prediction models for skin factor and flow efficiency.

The models are semi-empirical, which have been developed from the input of selected data generated from extensive experimental studies into filtration and formation damage[12,13] phenomena. All the analyses carried out on laboratory core tests were conducted under linear flow conditions, and upscaled into radial flow conditions, to simulate near-wellbore damage caused by particulate and filtrate invasion.

PRODUCTIVITY TOOL FORMULATION

Drilling Fluid Rheology. The rheological behavior of the drilling fluid has a major impact on pressure distribution in the wellbore and, hence, affects drilling overbalance pressure and fluid filtration. Therefore, to adequately predict downhole filtration, it is also necessary to predict downhole rheology.

Several studies of the HP-HT rheology of WBM and OBM have been presented in earlier papers[14,15]. Some of these studies which include many mathematical expressions are subjective. Politte[14] presented a multi-term equation with 13 numerical constants to model the viscosity of diesel oil. Houwen *et al.*[15] presented several equations to model rheological parameters. An API Bulletin[16] presented two equations to calculate pressure and temperature constants.

In this study, a different procedure has been adopted. Shear stress has been multiplied by a correction factor that depends on pressure and temperature. Then the rheological behavior and rheological parameters can be calculated from shear stress prediction at the pressure and temperature of interest. Two prediction models have been developed for WBM and OBM.

The models follow the general equation:

$$\tau_i = \tau_s[A_C \exp(AP - BT)] \qquad (1)$$

Where is the shear stress at depth of interest and the shear stress at standard conditions. The difference between the models is in respect of the empirical constants (A_C, A and B). Data used to evaluate the empirical constants have been obtained from selective HP-HT Fann-70 viscometer measurements.

The models often used to describe the behavior of the two fluids are Bingham Plastic[17], Power Law[18] and Herschel Bulkley models[19]. However, in this study the WBM and OBM rheological data are best described by the Herschel Bulkley model.

The main difference between OBM and WBM are the effects of pressure, which are more pronounced for OBM than WBM. For WBM the effect of pressure is very small, but is highly affected by an increase in temperature.

Temperature and pressure affect behavior and interactions of water or oil, clay, polymers and solids in mud. The effect of increasing the temperature of a liquid is to reduce the cohesive forces while simultaneously increasing the rate of molecular interchange. The former effect tends to cause a decrease of shear stress, while the latter causes an increase. The net result is that liquids show a reduction in viscosity with increasing temperature. The effect of increased pressure on OBM is to increase the cohesive forces, which tends to increase the viscosity.

Drilling Fluid Filtration. One of the major functions of a drilling fluid is the control of formation pressure. In order to prevent formation fluids from flowing into the borehole, the hydrostatic pressure of the mud column is usually made to exceed the formation pressure.

Wellbore differential pressure can cause excessive loss of liquid and associated drilling mud solids leading to potential permeability impairment of the formation, and contribute to borehole instability[20,21] and formation damage[22], especially in the HP-HT environment. The differential pressure depends on mud weight, fluid rheology and formation pressure.

As a result of overbalance pressure, the filter cake may form on sand face, through which only filtrate can pass, depending on the relationship between mud particle size distribution and formation pore size.

The process of drilling a well results in alternating periods, of varying duration, of dynamic and static filtration (sequential filtration). Dynamic filtration occurs when the mud is circulated; the cake thickness is the difference between the rate of deposition by filtration and the rate of erosion by circulating mud. The erosion rate of particles is proportional to the shear stress exerted by the circulating mud on the cake surface[23].

Static filtration occurs when the mud is not circulated, and the cake thickness increases as filtration continues.

The existing static and dynamic filtration[23,24] equations can be modified for downhole pressure and temperature conditions.

(i). *Static Filtration:*

Two prediction models have been developed for WBM and OBM. The models follow the general format:

$$t = Y_1V + Y_2V^2 \exp.\ (AP + BT) \qquad (2)$$

Where t is time and V the volume of filtrate. The difference between the models is in respect of the empirical constants (Y_1, Y_2, A and B).

(ii). *Dynamic Filtration:*

Two prediction models have been developed for WBM and OBM. The models follow the general format:

$$t = X_1 V - X_2(1 - e^{-X_3 V}) \exp.(AP + BT) \quad (3)$$

Equation (3) also can be used to predict dynamic from static filtration data. Since the modified filtration Equations (2) and (3) can predict the filtration coefficients (Y_1, Y_2, X_1, X_2 and X_3) therefore the filter cake characteristics such as cake resistance, permeability, porosity, etc. can be computed.

Filtration Pressure Drops. At the start of filtration, the pressure drop, ΔP_T, is across the sand face, but as the filter cake builds up more of the pressure drop is dissipated across the filter cake, P_C, and less across the sand face, P_f, thus.

$$\Delta P_T = \Delta P_f + \Delta P_C \quad (4)$$

Damage from Drilling Fluid. Formation damage mechanisms were studied extensively[25, 26]. However, formation damage from drilling fluid can be characterized by the thickness of filter cake, depth of solids and filtrate invasion and permeability reduction.

The two main damaging mechanisms which have been studied are particulate invasion during initial filtration period, and filtrate invasion through filter cake.

A. Filter Cake Build up

Filter cake thickness is given by:

$$\frac{dh_C}{dt} = \frac{\rho_f sV - K_\tau \tau}{(1 - ms)} \quad (5)$$

The shear stress should be calculated from rheological behavior of the mud Equation (1).

If the mud is not circulated then the shear stress τ is zero and the filter cake becomes thicker as static filtration continues.

B. Depth of Solids Invasion

Solids invasion occurs during initial filtration period. It is primarily a function of mud particle size distribution and the pore throat diameter of the formation. Semi-empirical equations have been developed for predicting the depth of solids invasion. These models are based on pressure drop in pipes and, therefore, involve the rheological behavior of the drilling fluid.

For Herschel Bulkley and Power Law fluids the model has been computed as:

$$L_S = \frac{C_1 \Delta P_f D_P^{(1+n)}}{K V_P^n (C_2 \frac{3n+1}{n})^n} \quad (6)$$

For Bingham Plastic fluid the equation is:

$$L_S = C_3 \Delta P_f \frac{D_P^2}{(C_4 \mu_P V_P + C_5 \tau_y D_P)} \quad (7)$$

These equations assume that the rheological properties of the fluid moving through the pore are the same as that of the bulk fluid. This assumption becomes increasingly invalid as the pore throat diameter decreases and mud components that affect the viscosity are screened out. In the limiting case, the viscosity is that of the filtrate.

As it can be observed from the above models, the depth of solids invasion requires the knowledge of the formation morphological characteristics such as permeability, porosity, tortuosity, *etc.*

Tortuosity (η) is the actual flow path and can be computed in laboratory from formation resistivity factor (F_R) and porosity thus:

$$F_R = a / \phi^b \quad (8)$$

$$\eta = \phi F_R \quad (9)$$

Then the mean pore throat diameter can then be calculated as:

$$D_p = 4.08 \, (\eta K / \phi)^{0.5} \quad (10)$$

C. Depth of Filtrate Invasion

The radius of filtrate invasion can be determined from filtration volume as:

Invasion in static condition:

$$r_f = \sqrt{r_w^2 + \frac{2r_w}{\phi}\left(\frac{-Y_1 t}{2Y_2} + \frac{(Y_1^2 + 4Y_2 t)^{1.5}}{12Y_2} - \frac{Y_1^3}{12Y_2}\right)} \quad (11)$$

Invasion in dynamic condition:

$$r_f = \sqrt{r_w^2 + \frac{2r_w t(1 - ms)K_\tau \tau}{\phi \rho_f s}} \quad (12)$$

All the parameters in equation (11&12) can be computed from sequential filtration experiments and Equations (2&3).

D. Permeability Damage

The initial formation permeability damaged in the zone occupied by particulate and filtrate is characterized by permeability reduction (damage) as a function of core length or distance from the wellbore in radial well flow conditions. The permeability damage factor can be described as:

$$C_F = k_d / k_f \quad (13)$$

The permeability alteration (k_d) can be computed from the knowledge of overall average permeability and total depth of invasion.

Productivity Evaluation

Well performance is reduced when near-wellbore formation is damaged. Key parameters in quantifying the formation damage or the reduction of the well productivity will be the skin factor or by the flow efficiency.

The skin factor s_d, defined as:

$$s_d = (1 - k_f / k_d) \ln (r_w/r_f) \quad (14)$$

Using a well productivity index (PI) usually represents well performance. Therefore, well flow efficiency due to near wellbore damage can be calculated as:

$$FE = PI_{actual} / PI_{ideal} \quad (15)$$

Then the damage factor can be computed from the reciprocal of the well flow efficiency.

$$DF = 1 / FE \quad (16)$$

PRODUCTIVITY TOOL STRUCTURE

In order to simulate the impact of drilling fluid filtration on well performance in terms of formation damage, a computer package with the models developed above is required. The structure of calculation is described as follows:

1. Input the data required for the models: wellbore parameters (hole geometry, casing size, *etc*), operating parameters (overbalance pressure, pump rate, *etc*), drill-in fluid parameters (mud type, rheology, *etc*) and formation parameters (permeability, porosity, *etc*).
2. Compute the rheological behavior at standard conditions and depth of interest.
3. Compute the rheological parameters and calculate the wellbore pressure distribution.
4. Compute the static and dynamic filtration and calculate filter cake properties.
5. Calculate the pressure drop across filter cake and sand face.
6. Quantify level of resultant damage by computing depth of solids and filtrate invasion, average permeability and permeability damage.
7. Evaluate the results of well performance by computing skin factor, ideal and actual productivity index, flow efficiency and damage factor.

APPLICATION OF THE PRODUCTIVITY TOOL

Specific case studies to illustrate the interpretation and practical usefulness of the productivity tool have been carried out using actual field data. The data are collected from four oil companies in North Africa (Table 1) and can be summarized as follows:

Table 1. Well summary.

Co.	Field	Well No.	TVD (ft)	Temp. (^{0}F)	Fluid type	Hole section (inch)	Completion
1	A	A1	14580	330	Oil based	8.50&6	cased
		A2	14500	322	Lignosulphonate	6	cased
2	B	B1	13528	320	Oil based	5.875	Openhole
		B2	13390	314	Lignosulphonate	8.50&5.875	Openhole
		B3	12245	280	Lignosulphonate	5.875	Openhole
3	C	C1	12370	290	Potassium chloride	8.50	cased
4	D	D1	10045	240	Dispersed polymer	8.50	cased

1. Seven wells with the total well depth ranging from 10045 ft to 14580 ft.
2. Reservoir sections drilled in 5.87, 6 and 8.50 inch holes.
3. Open hole and cased hole completions.
4. Wellbore pressure ranging from 5000 psi to 12800 psi.
5. Bottom hole temperature ranging from 240 ^{0}F to 330 ^{0}F.
6. Reservoir permeability ranging from 50 md to 400 md.
7. Oil-based and water-based drill-in fluids types (dispersed polymer mud, potassium chloride mud and lignosulphonate mud).

The application of the productivity tool has been used in two ways:

1. Evaluation Stage: The PRT simulated results have been evaluated against field data (post drilling):
   a) Predicted total wellbore pressure distribution versus field data (pump pressure).
   b) Predicted well performance in terms of formation damage against field measurements (depth of invasion from logging and skin factor from well test data).
2. Planning stage: The PRT has been used for fluid optimization and selection against different operating parameters, such as fluid type, rheology, pressure, *etc*.

Evaluation Stage. Table 2 illustrates the predicted total wellbore pressure distribution versus field data

Table 2. Predicted pump pressure versus field data (pump pressure).

Pump Pressure (psi)

Well number	Total depth (ft)	Hole section (inch)	BHtemp (^{0}F)	Field data (Psi)	PRT prediction (Psi)
A1	13790	8.50	315	2575	2466
	14580	6	330	1780	1670
A2	14500	6	322	1700	1695
B1	13528	5.875	320	2000	2032
B2	12175	8.50	305	2600	2820
	13390	5.875	314	2000	2083
B3	12245	5.875	280	1500	1566
C1	12370	8.50	290	2850	3000
D1	10045	8.50	240	1950	2092

(pump pressure). The prediction shows agreement with field data. Table 3 shows predicted (depth of invasion and skin factor) against field measurements. The field measurement from well test data gives the total skin and the PRT predicts the drilling skin. However, stochastic analyses have been carried out based on standard assumptions to calculate both the partial completion skin and perforation skin and add them to the drilling skin predicted from the PRT, in order to enable comparison with field test data. Table 4 shows agreement between the PRT predicted skin and field measurement.

Table 3. Formation damage predicted against field measurement.

				Depth of Invasion (inches)		Skin	
Well No.	TVD (ft)	Hole (inch)	BHT (^{0}F)	Field data	PRT prediction	Field data total skin	PRT prediction drilling skin
A1	14580	6	330	40	34.79	9.00	4.11
A2	14500	6	322	60	77.73	12.0	5.24
B1	13528	5.875	320	60	45.43	10.0	4.00
B2	13390	5.875	314	70	92.73	10.0	5.87
B3	12245	5.875	280	70	90.81	10.0	5.63
C1	12370	8.50	290	60	77.63	9.00	4.48
D1	10045	8.50	240	40	48.69	8.00	3.62

Table 4. Formation damage predicted against field measurement.

Well No.	TVD	Mud type	Field data Total skin	PRT prediction Sd	Sc+Sp	Total Skin
A1	14580	OBM	9.00	4.11	3.10	7.21
A2	14500	CL/CLS	12.00	5.24	3.32	8.56
C1	12370	KCl	9.00	4.48	2.84	7.32
D1	10045	PWBM	8.00	3.62	2.61	6.23

Planning Stage. The input data are from well number (A1) for a 6 inch hole section and the

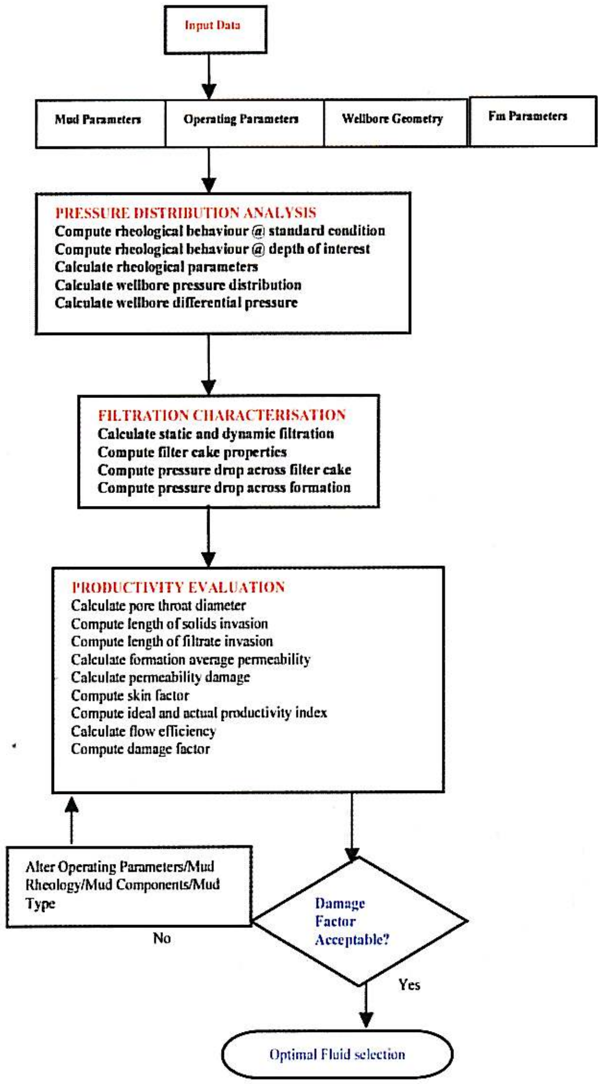

Fig. 1. Shows a flow chart on which the productivity tool has been developed.

assumption was made to select the best HP-HT drilling fluid to drill this well with minimum formation damage. The types of the drilling fluids that have been used for evaluation are oil-based and water-based muds (dispersed polymer mud, potassium chloride mud and lignosulphonate mud). The fluid rheology and mud composition data for these types of mud have been used from field data of six wells drilled by various oil companies.

Figures 2 to 8 illustrate the effects of different parameters such as rheological behavior, drilling time, temperature, and overbalance pressure on flow efficiency comparing different types of WBM and OBM drill-in fluids. Three different rheological properties for both OBM and WBM have been used for fluid selection of this particular well (A1).

OPTIMIZATION PROCESS

Effect of Rheological Parameters. Figures 2 and 3 show that an increase in rheological parameters (yield stress and consistency index) results in an increase in depth of filtrate invasion and, hence, an increase in damage factor.

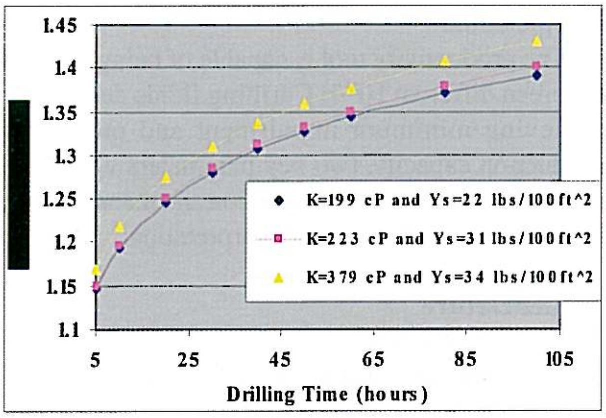

Fig. 2. Effect of rheology on formation damage for OBM.

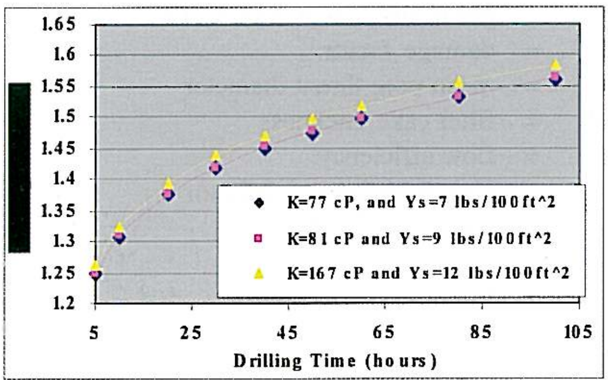

Fig. 3. Effect of rheology on formation damage for WBM.

Effect of Rheological Characterisation. Figure 4 shows the depth of invasion profile for WBM and OBM. The figure also shows the accurate description of the rheological behavior of the drill-in fluid required to accurately predict the depth of invasion.

Figure 4 illustrates effect of rheological behavior on formation damage characterization. A comparison has been made between the actual fluid rheological behavior models, i.e. Herschel-Bulkley, Power Law and Bingham Plastic models. The figure shows that the Bingham model predicts

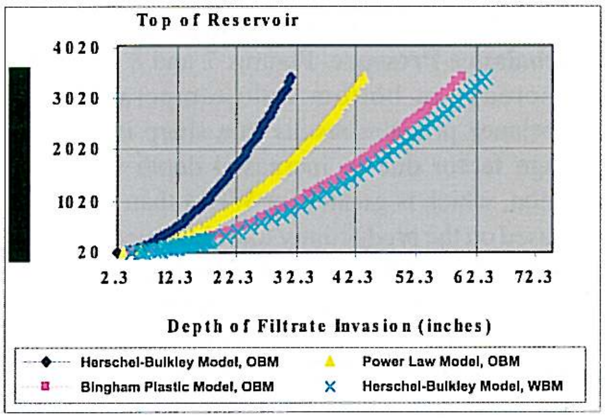

Fig. 4. Effect of rheology characterisation on depth of invasion.

higher formation damage than the actual model. The Herschel-Bulkley model best represents actual fluid rheology. The depth of invasion was found to be greater for WBM than OBM. Figure 5 shows damage profile using OBM.

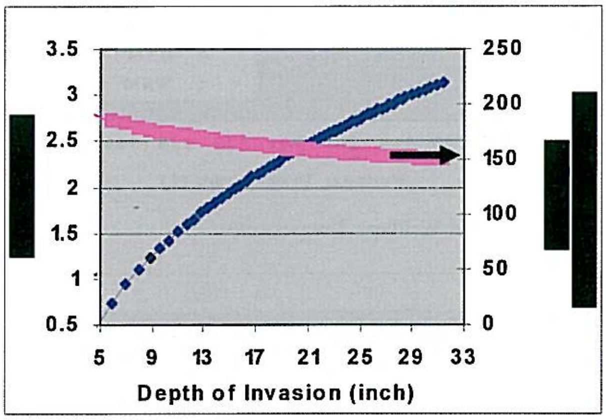

Fig. 5. Damage profile using OBM.

Effect of Drilling Time. Figure 6 shows an increase in drilling operational time results in an increase in depth of filtrate invasion and, hence, an increase in damage factor, which is greater for WBM than OBM.

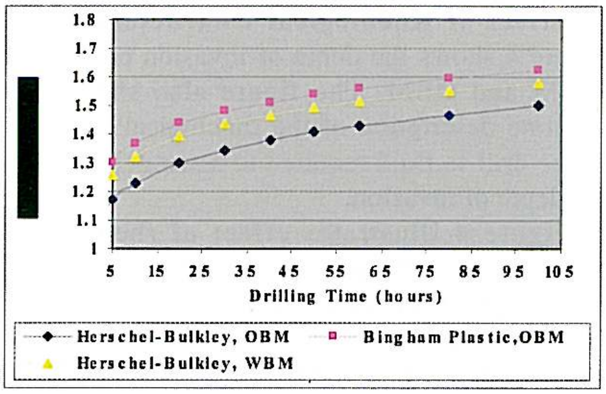

Fig. 6. Effect of Drilling Time.

Effect of Wellbore Temperature and Overbalance Pressure. Figures 7 and 8 show that an increase in bottom hole temperature and overbalance pressure results in a sharp increase in damage factor due to increased depth of filtrate invasion, which is greater for WBM than OBM.

Based on the productivity tool simulated analysis, the selection of OBM with rheological parameters [n= 0.66, K= 199 cp and Ys=22 lb/100ft^2] to drill this particular well (A1) gives more advantages for well flow performance than for WBM.

However, it is necessary during the fluid design stage to screen different HP-HT fluids also based on a higher percentage of the return permeability test. This is because the depth of invasion is inversely proportional with percentage of the return permeability test[27].

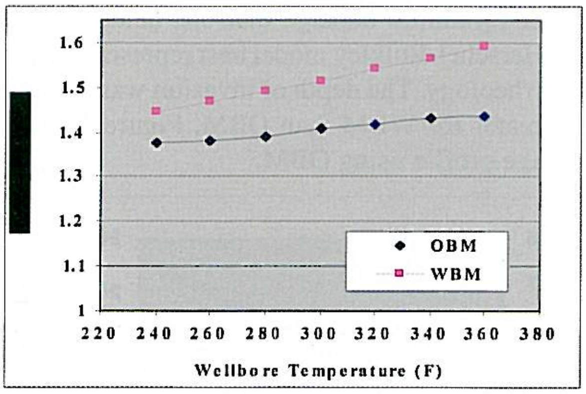

Fig. 7 - Effect of Wellbore Temperature.

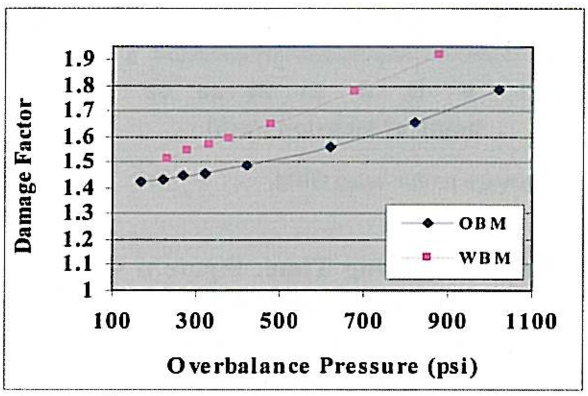

Fig. 8 - Effect of Overbalance Pressure.

CONCLUSIONS

The field application of the productivity tool is presented to simulate impact of drilling fluid filtration on formation productivity in an HP-HT environment. The productivity tool can be used for predicting formation damage mechanisms caused by particulate and filtrate invasion.

The tool can evaluate formation damage in laboratory as linear-flow core tests and can be converted to radial-flow scale for oil field applications.

Input requirements include parameters such as hole geometry, BHA configuration, mud type, composition, rheology data and formation characteristics.

The productivity tool can be used to investigate the influence of many parameters on the well flow performance.

The tool can be used before drilling as a design (planning) tool, and during drilling and post drilling as evaluation and comparison tool with well test data interpretation.

The productivity tool is capable of being utilized to screen different HP-HT drilling fluids desired for achieving minimum impairment and maximum production capacity, two key parameters which are relevant to optimum fluid selection and management, in addition to well test data interpretation.

Nomenclature

a, b = coefficients
A, B = pressure and temperature coefficients
A_c = constant
C1, C2, C3, C4, C5 = constants
C_F = permeability reduction factor
DF = damage factor
D_p = mean pore throat diameter
dh_c = filter cake thickness
FE = flow efficiency
F_R = resistivity formation factor
k = consistency index
k_τ = erodability coefficient
k_f = formation permeability
k_d = permeability damage
L_S = depth of solids invasion
m = ratio of wet to dry cake

n = Power law index
P = applied pressure
PI_{actual} = productivity index after formation damage
PI_{ideal} = productivity index before formation damage
ΔP_T = total differential pressure
ΔP_f = pressure across formation
ΔP_c = pressure across filter cake
r_f = radius of filtrate invasion
r_w = wellbore radius
s = solids concentration
s_c = partial completion skin
s_d = drilling skin factor
s_p = perforation skin
t = time
T = temperature
V = filtrate volume
V_p = velocity in porous medium filtration coefficients
Ys = yield stress

Greek Symbols

η = tortuosity
μ_P = plastic viscosity
τ_y = yield point
τ_s = shear stress at standard condition
τ_i = shear stress at depth of interest
ϕ = porosity of formation
ρ_f = density of filtrate

Acronyms

BHA = bottom hole assembly
BHT = bottom hole temperature
Cl/Cls = lignosulphonate mud
KCl = potassium chloride mud
PWBM = dispersed polymer mud
LP-LT = low pressure-low temperature
HP-HT = high pressure-high temperature
OBM = oil-based mud
md = millidarcy
TVD = total vertical depth
WBM = water-based mud

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