SCAL : AN INDISPENSABLE STEP FOR FORMATION DAMAGE EVALUATION

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Abstract

The impact of wellbore formation damage on the economic viability of a field development is becoming increasingly widely accepted by the oil industry. Productivity losses due to permeability damage generated by drilling and completion operations are of main concern specially for long horizontal open hole completed wells in which the near wellbore damage is not by-passed by perforations. Formation damage evaluation from specific laboratory tests becomes a large part of the SCAL activities and many papers have focussed on this area of research.

This paper is a contribution to i) understand mechanisms of drilling mud and mud filtrate invasion, ii) quantify drilling-induced permeability damage and iii) evaluate the performance of various cleanup procedures to restore the near wellbore flow properties.

Specific laboratory equipment and procedures derived from techniques used in SCAL were developed to evaluate filtration properties of drilling muds and permeability damage generated by the wellbore invasion. The performance of 8 mud formulations (Water-Based Mud (WBM) and Invert Emulsion Mud (IEM)) was evaluated on 40 cm long sandstone core samples. Then, a comparative study aimed at determining the efficiency of various cleanup treatments using specific “breakers” to remediate filter cakes has been performed on core samples damaged either with a polymeric Water-Based Mud or an Invert Emulsion Mud. Results shows that the IEM’s present better filtration properties and are less damaging than the WBM’s tested here. Specific WBM “breakers” (enzymes, oxidants) are efficient and may restore a large part of the initial damage. On the other hand, breakers for IEM (surfactants, emulsified acid, solvents) may create additional damage if the breaker is allowed to invade the formation.

Finally, some recommendations are given to design laboratory tests for evaluating drilling-induced formation damage and for restoring near wellbore flow properties.

Introduction

Among the different tasks which constitute an effective integrated reservoir management approach, the role of laboratory measurements of rock flow properties is certainly one of the most valuable as the reservoir simulations getting always more detailed will use more and more directly the data obtained from Special Core Analysis Laboratory (SCAL) task. In particular, estimations of well productivity and injectivity become an important part of SCAL activities.

It is well recognised that near wellbore flow properties are altered by mud and mud filtrate invasion during overbalanced drilling operations[1]. The degree of alteration, generally called “Formation damage” depends upon a large number of parameters such as nature and characteristics of the drilling mud, formation properties and operating conditions (shear rate applied on the mud, overbalance pressure, temperature, etc.) Formation damage due to drilling fluid invasion may create substantial reductions in oil and gas productivity in many reservoirs. Productivity losses are especially critical for long horizontal wells which are often “open hole” completed. In such a case, the near wellbore damage is not by-passed by perforations and may create very large skin values. As an example, **Figure 1** presents the results of theoretical calculations of the variations of oil flow rate for a long horizontal well designed to produce initially 12000 BOPD. The impact of near wellbore invasion on the actual flow rate was quantified through two parameters: depth of filtrate invasion and permeability reduction in the invaded zone.

For instance, with a depth of invasion of about 16 inches and a permeability reduction of 90% in the invaded zone, one can see on **Figure 1** that oil deliverability of the well is divided by a factor of 2 (6000 instead of 12000 BOPD).

The economic impact of poor productivity of open hole wells has pushed toward significant efforts in recent years to improve laboratory testing methods for assessing drilling induced permeability damage and for evaluating the best cleanup product to remove near wellbore damage.

This paper describes a laboratory methodology developed at IFP during these last five years in order to mimic the process of drilling mud invasion on long core samples and to characterise the related permeability damage. The results of a phenomenological study performed on long core samples to evaluate filtration properties and permeability damage generated by 8 typical drilling mud formulations are presented and discussed.

The experimental approach allows us also to model near wellbore cleanup treatments using specific “breakers” to remediate the filter cakes generated by drilling fluids. A comparative cleanup study has been performed on sandstone core samples damaged either with a typical polymeric water-based mud formulation or an Invert Emulsion Mud. Various specific breakers treatments were tested to evaluate their ability to remediate the filter cakes and to restore the flowing properties. Oil Return Permeabilities were measured firstly to quantify the damage after mud exposure and, then, after cleanup treatment to evaluate breakers efficiency.

Conceptualization of Drilling Mud Damage

As soon as the drilling bit comes into in contact with the reservoir, there is as rapid whole mud invasion (spurt loss) since no filter cake protects the pay zone. Then, an internal filter cake is built and the mud filtrate displaces the reservoir fluids under the overbalance pressure. Finally, an external filter cake is established and a steady-state situation characterized by a constant filtration flow rate and a constant thickness of external filter cake is generally observed, as schematically depicted in **Figure 2**. This dynamic equilibrium results from the stopping of particle deposition due to the shearing action of the drilling fluid. These considerations show that it is of prime importance to evaluate the filtration properties from tests under dynamic conditions i.e. with a specific design of the core-holder cell allowing to circulate the mud across the inlet face of the core sample.

Development of Enhanced Laboratory Testing Procedure

In the past a great number of experimental studies have been conducted to assess mud filtration properties, drilling-induced damage and to evaluate cake lift off pressures and cleanup techniques[2-10]. But generally these studies were conducted on small piece of core samples (2 to 5 cm), on metallic porous disks or sometimes on filter papers initially saturated with brine only and under operating conditions quite far from those prevailing in wells (pressure, temperature, shear rate, etc.). More recently a comparative study was performed in order to establish a standardized methodology for formation damage testing[11]. The results, obtained on short cores on which a large dispersion of fluid losses (spurt and filtration rates) was observed, showed that a good level of repeatability and/or reproducibility has not been achieved. Significant improvements were proposed, specially for restoring connate water saturation prior to the tests and determining oil return permeability to assess residual permeability impairment.

- Laboratory Equipment for Dynamic Mud Leak off Tests on Long Core Samples

The equipment developed at IFP is depicted in **Figure 3**. It mainly includes:

- a dynamic filtration core-holder cell which can accommodate samples of 5 cm in diameter and up to 40 cm long. The cell is equipped with five pressure taps located at 5, 10, 15, 20 and 25 cm from the inlet face of the core. Special care was taken to design the end-piece of cell. A rectangular channel through which the mud flows parallel to the inlet face allows to obtain a steady shear rate on the deposited mud cake. Pressure taps allow to monitor the pressure drops across six sections of the core while circulating the mud and while backflushing the oil to simulate the well production. This allows us to calculate permeability impairment as a function of the distance from the damaged face of the core.
- a mud circulating system including a rotary diaphragm pump to generate laboratory mud flow rates (up to 11 L/min) which represent typical mud velocities occurring in the well, a back pressure regulator valve and various dampeners and mud containers. For example, well mud flow rates may vary from 600 to 4000 L/min depending on the hole and on the drill pipe diameters. These flow rates induce typical shear rates ranging from 100 to 700 s-1. Considering the maximum flow rate of the mud pump (11 L/min) and the core diameter which can be accomodated in our device (5 cm), the maximum laboratory shear rate value was about 500 s-1.
- an oil and brine injection device including a positive displacement pump and cells which contain oil and brine to saturate the core and measure oil return permeabilities.
- various measurement systems including temperature and pressure transducers and an automatic weighting device for the effluent production.
- an automatic computer controlled data acquisition system.

- Experimental Procedures

The first part of the paper reports the results obtained from experiments performed on 40 cm long core samples (high permeability Vosges sandstone) to test the methodology and to evaluate the performance of various mud formulations under bore hole conditions. The second part presents the results obtained on 10 cm long core samples (Vosges and Berea sandstones) to test the cleanup procedures. All cores were cut parallel to the bedding plane in blocks of Vosges and Berea sandstones. After CT Scanning examinations to check their homogeneity, the selected core samples were cleaned, dried and their gas permeability, kg was measured. Then, the cores were evacuated and saturated with a 20 g/L NaCl brine. Pore volume and brine permeability were measured. Connate water saturation, Swi, was established by flooding the cores with a viscous mineral oil (Azola 46, μo = 110 cP at 20°C) up to 600 cm^3/hour. Values of Swi were ranging from 20.6 to 27.4% for Vosges sandstones and from 19 to 31% for Berea sandstone depending on the permeability. Then the viscous oil was miscibly displaced at low flow rate (10 cm^3/hour) with Soltrol 130 (μo = 1.6 cP at 20°C) until stabilization. Finally, oil permeability at Swi was measured at three flow rates and taken as reference “undamaged” initial permeability.

- Mud Formulations and Breakers Tested

Study 1: Performance Evaluation of Various Drilling Fluids

The purpose of the study 1 was to evaluate the filtration characteristics and the permeability damage of various mud formulations which could be used to drill a high-permeability sandstone reservoir containing a light oil. The final objective was to select the less damaging fluid for such a reservoir.

Five typical water-based muds (F1 to F5 in Table 1) were selected to cover a large range of rheological and filtration properties. Formulation F1 is a standard salted polymeric/bentonite mud. Formulation F2 is a mud usually used for clay swelling inhibition. It contains polyglycerol, encapsulating agent (PHPA), a fluid loss reducer (PAC) and bentonite. Mud formulations F3 and F4 are proposed for high pressure and temperature conditions (HP-HT). They are non-weighted and weighted, respectively, with 780 g/L of barite. These two formulations contain bentonite, a mineral viscosifier, a sulfonated terpolymer as fluid loss reducer, a dispersant and OCMA clay as drilled solids. Formulation F5 is a mixed metal hydroxide (MMH) mud formulated with bentonite, modified polysaccharide and $CaCO_3$, for bridging and weight control.

Table 1 - Water-Based Muds: Compositions & Properties

Composition (g/L)	Drilling Mud				
	F1	**F2**	**F3**	**F4**	**F5**
Distillated water	As requested for one liter of mud				
Xanthan	1.5				
PAC reg.	3.0	3.0			
NaCl	5.0	5.0			
KCl	40.0				
Polyglycerol		75.0			
PHPA		2.0			
MMH					3.0
Synthetic Clay			4.2	4.2	
Sulfonated Polymer			10.0	10.0	17.0
Dispersing Polymer			19.0	19.0	
OCMA clay			50.0	50.0	
$CaCO_3$ (D_{50}=75µm)					48.5
$CaCO_3$ (D_{50}=150µm)					28.5
Bentonite	30.0	30.0	19.0	19.0	28.0
Barite				780	
Specific gravity (g/cm^3)	1.02	1.02	1.01	1.50	1.09
A.V. (mPa.s)	20	29	52	95	63
P. V. (mPa.s)	12	21	38	82	41
Y. V. (lb/ft^2)	16	16	28	26	43
API Filtrate (cm^3)	12.0	7.0	5.2	3.0	6.2

Table 2 – Invert Emulsion Muds: Compositions and Properties

Composition (g/L)	Drilling Mud		
	F6	**F7**	**F8**
Oil HDF200	453.0		
α-Olefine		413	
Ester			476.8
Sea Water		279	124.0
Water	140.6		
$CaCl_2$	89.2		27.0
Lime	28.6	16.0	1.0
Primary Emulsifier (surfactants)	28.6	29.0	10.0
Secondary Emulsifier (surfactants)	17.1	5.0	6.0
Organic Clay Viscosifier	10.0	15.0	6.0
Polymeric Fluid Loss Reducer		4.0	6.0
Barite	630.6	522	600.0
Specific gravity (g/cm^3)	1.50	1.35	1.35
A.V. (mPa.s)	42	40	42
P.V. (mPa.s)	38	26	36
Y.V. (lb/100 ft^2)	7	27	12
HP/HT Filtrate* (cm^3)	8.0	4.5	6.0

* 35 bar, 120°C (F6) - 35 bar, 90°C (F7 and F8)

Table2 gives the characteristics of the three selected OBM formulations. Actually the OBM muds were Invert Emulsion Muds (IEM) in which the continuous phase is the oil. Formulation F6 is a low toxicity IEM where the oil phase is a viscous oil (HDF200), weighted with barite. Formulations F7 and F8 are “green” IEM where the base oil is an alphaolephine (F7) and an ester synthetized from vegetable oil (F8). For F7 and F8 formulations, barite was added to reach a specific gravity of 1.35 g/cm^3.

Study2: Near Wellbore Cleanup Efficiency

The study 2 was undertaken to provide elements to answer the following question: "Is it always necessary to use a cleanup procedure with a breaker to remediate filter cakes for increasing the well productivity ?". Two typical mud formulations were selected to damage the core samples : an IEM and a WBM, both weighted with the same solids size ($CaCO_3$, D_{50} = 5.2 μ), to reach a specific gravity of 1.10 g/cm3. The compositions, rheological and filtration properties are given in Table 3 (WBM) and in Table 4 (IEM).

Table 3 – Water-Based Mud - Composition	
Components	**g/L**
Distillated Water	930.0
KCl	55.0
BiopolymerViscosifier	11.0
Modified Starch Filtrate reducer	14.0
pH Buffer	1.0
Weighting agent: $CaCO_3$ (D_{50} = 5.2 μ)	150.0
Mud Properties at 50°C	
Specific gravity (g/cm^3)	1.10
A.V. (mPa.s)	23
P.V. (mPa.s)	10
Y.V. (lb/100 ft^2)	26
API Filtrate (cm^3)	4.5
HP/HT Filtrate (cm^3, at 70°C, 500psi)	11.0

Table 4 – OBM (Invert Emulsion Mud) - Composition	
Components	**g/L**
Brine (20% CaCl2)	331.4
Oil Base EDC95	482.4
Primary Emulsifier (Carbotec)	24.0
Secondary Emulsifier (Carbomul)	4.9
Organic Clay Viscosifier	20.0
Weighting agent: $CaCO_3$ (D_{50} = 5.2 μ)	220.0
Mud Properties at 65°C	
Specific gravity (g/cm^3)	1.10
A.V. (mPa.s)	21
P.V. (mPa.s)	19
Y.V. (lb/100 ft^2)	5
API Filtrate (cm^3)	-
HP/HT Filtrate* (cm^3 at 80°C, 500psi)	2.6

After completion of mud leak off tests, the mud in the inlet end piece of the core holder cell was displaced and the breaker solution was applied under static overbalance pressure of 20 bars. Fluid loss was continuously monitored to follow the process of filter cake destructuration. Then oil return permeability was mesured by blackflushing oil at different oil flow rates to evaluate the efficiency of the breaker application. **Figure 4** shows a typical fluid loss curve during a breaker test. The curve is always composed of two parts a) external filter cake invasion with a low rate, and b) core sample invasion at high rate. The change in slope is used to determine the critical contact time (CCT) for the breaker to go through the filtercake. This concept has been introduced to evaluate the soaking time after which the breaker was allowed to invade the formation.

Among the different products proposed by Services companies, we decided to test 2 WBM breakers (an oxidizing agent, NaOCl and a starch specific Enzyme, both in solution in brine (KCl 20 g/L) and 3 OBM breakers (a mixture of organic solvents, EGMBE, an emulsified HCl solution and a mixture of surfactants). Their compositions are given in Table 5.

Table 5 – Compositions of "Breaker" Solutions

Water-Based Mud

- Oxidizer : NaOCl at 5% in KCl 20 g/L
- Starch-Enzyme : 10% in KCl 20 g/L

Invert Emulsion Mud

- Organic Solvents : Ethylene-Glycol-Monobutylether (EGMBE), 5% concentration in NH_4 (30 g/L)
- Emulsified Acid : 48.5% HCL5x, 50% Toluene, 1.5% Emulsifier
- Surfactants (ABCS) : 0.2 g/L Di-Octyl Sulfonate, 0.1 g/L Non-Ionic Surfactant, 5%Ethanol in NH_4 Cl (30 g/L)

- Mud Leak Off Tests and Return Permeability Measurements

The main operating conditions were as follows for both studies.

	Temperature	Overbalance Pressure	Mud Time Exposure	Shear Rate	Oil Back Flow Rate
Study 1	80°C	15 bars (WBM) 40 bars (IEM)	20-60 hr	50 s^{-1}	300 cm^3/hr
Study 2	60°C	20 bars (WBM) 50 bars (IEM)	1-4 hr + 16-24 hr	180 s^{-1} static	10 and 300 cm^3/hr

For the study 1, dynamic mud leak off tests were performed at moderate shear rate (50 s^{-1}) until breakthrough of mud filtrate at the outlet face of the long core samples. Then a relatively high oil back flow rate (300 cm^3/hr) was applied to measure return permeabilities. This flow rate generates a Darcy's velocity of about 3.6 m/day, similar to the one occurring in a standard vertical well.

For the study 2, a static mud filtration period of 16-24 hr was also performed after dynamic mud invasion at high shear rate (180 s^{-1}) to simulate what happens when the well is left under overbalance pressure without mud circulation. The total amount of fluid losses for both filtration periods varied from 0.7 to 0.8 PV. Then, a low oil back flow rate (10 cm^3/hr) was applied to generate an oil velocity representative of the production of a long horizontal well producing 1000 m^3/day. Finally, the oil flow rate was increased up to 300 cm^3/hr to simulate what happens if the oil flows through a limited length of the open hole well. According to the analysis of Alfenore et al.[12], oil return permeabilities measured at 10 cm^3/hr are called Initial Return Permeability (IRP) and those measured at 300 cm^3/hr are called Ultimate Return Permeability (URP). IRP is the return permeability obtained at the beginning of the production under low drawdown pressure and URP is the return permeability obtained after a long production period under high drawdown pressure.The latest value quantify the residual damage which can be expected.

Presentation and Discussion of the Results

Study 1: Performance Evaluation of Various Drilling Fluids.

Table 6 presents the main petrophysical characteristics of the 8 long sandstone core samples, the filtration characteristics and the global return permeabilities obtained.

- Comparison of the filtration properties.

The kinetics of mud filtration is an important parameter in terms of wellbore invasion since both spurt losses and stabilized rates of filtrate invasion directly impact the depth of invasion. For a given time of mud exposure, the higher the losses, the larger the depth of invasion. Two observations arose from the comparison of all filtration curves reported in **Figure 5** i) spurt volume and rate of filtration largely vary from one to another formulations, and ii) IEM formulations showed better filtration properties than the WBM tested here. In particular, extremely low values of spurt loss and filtration rate were found for the F6 formulation (i.e. spurt loss close to zero and filtration rate 6 times lower than the one obtained with the best WBM formulation F5. Note that the sophisticated F3 and F4 WBM muds did not give better filtration rates than the standard polymeric WBM F1. Intermediate values were obtained with both IEM muds F6 and F7 (Table 6).

Table 6 – Dynamic Mud Leak Off Tests and Return Permeabilities on Long Core Samples High Permeability Vosges Sandstone – WBM (F1 to F5) – IEM (F6 to F8)									
kg (md)	ϕ (%)	Swi (%)	ko at Swi (md)	Mud	Spurt Loss (cm^3/cm^2)	Filtration Rate (10^{-3} cm/min.)	Global Return Perm. (% initial)	Swr (%)	ΔSw = Swr - Swi
3300	23.5	20.6	2130	F1	1.39	2.6	35	37	16
1456	22.8	25.1	1005	F2	1.29	1.5	28	49	24
2105	21.2	23.8	1347	F3	0.60	4.8	11	41	17
2274	21.4	24.0	1487	F4	0.55	3.5	15	49	25
2987	23.2	25.0	2178	F5	0.56	1.4	39	36	11
1139	22.0	25.4	1166	F6	~ 0	0.24	68	n.a	n.a
1285	23.7	25.0	1195	F7	0.17	0.70	80	n.a	n.a
1689	21.7	27.4	1392	F8	0.28	0.15	94	n.a	n.a

- Comparison of permeability damage

The oil return permeabilities obtained for each section of the long core samples are reported in Table 7. These values quantify the residual damage after injection of many pore volumes of oil at relatively high flow rate (300 cm^3/hr). One can see that the damage was always severe in the first 5 cm of the core with all the WBM tested since return permeabilitites were ranging from 8 to 22% of initial permeability. Global values (0-40 cm) of return permeabilities are also reported in the last column of Table 7. The best performance among the 5 WBM was obtained with the F5 formulation which gave 39% of return permeability. Note that the standard F1 formulation presented also an acceptable performance (35% return permeability). Concerning the IEM formulations, it is interesting to note that all the three muds tested gave higher return permeabilities ranging from 68 to 94%. To visualize the comparative performances we have plotted in **Figure 6** the oil return permeabilities as a function of the distance from the inlet face of the core. The left graph presents average values obtained with the 5 WBM formulations, leading to a global return permeability of 26%. On the other two graphs of **Figure 6** data obtained with the F6, F7 and F8 formulations are reported.

Table 7 – Dynamic Filtration Tests on Long Cores (40 cm)							
Mud Formulation	Oil Return Permeability (% initial)						
	0-5 cm	5-10 cm	10-15 cm	15-20 cm	20-25 cm	25-40 cm	Global
F1	8	20	63	88	96	100	35
F2	12	16	23	38	51	66	28
F3	11	12	14	12	11	9	11
F4	22	22	14	11	7	20	15
F5	10	25	30	88	60	97	39
Invert Emulsion Muds							
F6	23	98	127	117	113	84	68
F7	48	79	80	101	115	85	80
F8	42	89	155	152	123	118	94

One can see that oil return permeabilities are greater than 100% at intermediate distances from wellbore (between 10 and 30 cm depending on the mud). This is particularly spectacular with the F8 formulation since oil return permeability reaches a value of about 150% between 10 and 20 cm from the wellbore. Note that these values were calculated in percentage of global oil permeability (0-40 cm) in presence of Swi. The significant increase of return permeability at that distance may be due to local permeability heterogeneity.Another possible explanation of this stimulation effect may be found through a reduction of connate water saturation during filtrate invasion leading to a favourable relative permeability effect during oil back flow process.

As demonstrated earlier by Ballard and Dawe[13], the presence of surfactants and emulsifiers in invert emulsion oil-based muds can cause emulsification and migration of connate water, thus reducing the water saturation as well as inducing the alteration of the wettability of the pore walls[14]. In our study no specific attempt was made to evaluate the potential changes in wettability, but rather we tried to determine the effect of surfactants used in F7 and F8 formulations on the brine-filtrate interfacial tensions (IFT).

A series of IFT measurements was performed on equilibrated phases (20 g/L NaCl and reconstituted filtrates) at ambient temperature using the Wilhelmy plate or spinning-drop method, depending on the magnitude of the IFT. Simplified filtrates were reconstituted with each specific base oil and surfactants used in both formulations. Two surfactant concentrations were studied to evaluate the IFT variation with the surfactant content in the mud filtrate. Results are given in Table 8.

Table 8 – Interfacial Tension (IFT), mN/m

F7	Formulation	
	Base Oil/Brine	17.9
	Base Oil+7.33 g/L Surfactant/Brine	0.4
	Base Oil+3.65 g/L Surfactant/Brine	0.6
F8	Formulation	
	Base Oil/Brine	10.7
	Base Oil+2.18 g/L Surfactant/Brine	0.9
	Base Oil+1.09 g/L Surfactant/Brine	1.3

From these measurements one can see that the presence of surfactant dramatically decreases IFT values even at moderate concentration. For instance, with the F7 formulation, IFT decreases by a factor of 45 (17.9 down to 0.4 mN/m) with the maximum surfactant concentration and by a factor of 30 with a half time the initial concentration (from 17.9 down to 0.6 mN/m). A similar trend was observed with the F8 formulation. However the variation was slightly less important (from 10.7 down to 1.3 or 0.9 mN/m, depending on surfactant concentration). These measurements suggest that the capillary forces may be considerably reduced during filtrate invasion and then during oil backflow. Thus, the wetting phase (connate brine), initially trapped, may be reduced, inducing a better mobility of oil due to a favorable relative permeability effect. Obviously this aspect should be confirmed by specific coreflood tests, but our results are in agreement with the findings of Sanner and Azar[15] obtained on sandstone and carbonate cores.

The poor performance of the WBM may be explained by a partial trapping of wetting phase (filtrate) during oil back flow (See right column of Table 6). Swr values were calculated from volumetric balance between injected and produced fluids. This effect is illustrated in Figure 7 which presents a typical set of relative permeability curves during imbibition (filtrate invasion) and then, during a second drainage process (oil back flow). One can see that a trapped wetting phase saturation of 20% may induce a significant reduction in oil relative permeability.

Study 2: Near Wellbore Cleanup Efficiencies

Table 9 presents the results of the 4 tests performed on high and on medium permeability sandstone core samples damaged with the WBM, together with the main petrophysical characteristics of the samples. For each test are reported the values of IRP and URP obtained first by natural cleanup (oil back flow) and, then, by oil back flow after breaker application. The values of critical contact time (CCT) are also reported in Table 9. To illustrate the determination of CCT values, the **Figure 8** presents the comparative fluid loss curves obtained with the 3 IEM breakers. One can see on Table 9 that both IRP and URP values are better after breaker application for both breakers. This confirmed that a specific cleanup procedure after drilling with a WBM may be very efficient, since a gain of ultimate return permeability ranging from 10 to 26% was obtained depending on the initial permeability and the nature of the breaker. To illustrate this effect, IRP and URP values are compared on **Figure 9**. This Figure shows that the best breaker efficiency was obtained on the high permeability samples on which the initial mud damage was relatively important.

Table 9 – WBM – Mud Leak Off Tests Followed by Cleanup Treatment (Breakers)

kg	ϕ	Swi	ko at Swi	Oil Return Permeability				Type of	
				After Natural Cleanup		After Breaker Cleanup			
(md)	(%)	(%)	(md)	IRP (%)	URP (%)	IRP (%)	URP (%)	Breaker	C.C.T (min.)
1404	23.0	31	1506	5.1	11.0	3.6	37.2	NaOCl 5%	10
611	22.4	22	651	6.2	39.3	10.1	49.0	NaOCl 5%	16
1852	23.7	31	1544	4.9	13.0	5.7	29.8	Enzyme 10%	150
318	22.3	25	170	7.1	58.0	15.3	83.0	Enzyme 10%	150

Table 10 – IEM – Mud Leak Off Tests Followed by Cleanup Treatment (Breakers)

kg	ϕ	Swi	ko at Swi	Oil Return Permeability				Type of	
				After Natural Cleanup		After Breaker Cleanup			
(md)	(%)	(%)	(md)	IRP (%)	URP (%)	IRP (%)	URP (%)	Breaker	C.C.T (min.)
1505	23.7	19	1584	9.8	31.0	3.8	24.8	EGMBE	26
314	22.6	25	251	58.1	60.1	9.8	50.0	EGMBE	180
1308	23.0	31	1372	10.2	30.4	1.4	10.2	Emuls. Acid	4
680	22.9	24	648	28.0	52.1	1.5	22.4	Emuls. Acid	16
1430	23.2	27	1331	10.3	30.1	2.0	6.5	Surfactants	300
407	22.5	31	613	27.0	51.4	9.0	29.5	Surfactants	150

On Table 10 are presented in a similar way the results obtained with the IEM breakers. One can see that the IEM damage is generally less important (IRP values ranging between 10-28% and URP values ranging between 30-60% depending on the permeability). But after cleanup with a breaker, a detrimental effect was observed since IRP and URP values were less than the ones obtained after natural cleanup. This is illustrated on the **Figure 10** on which we can see that all the three breakers tested gave an additional damaging effect ranging from 6 to 48% for IRP values and from 7 to 30% for the URP values. In such a case, the use of an IEM breaker may be very detrimental for the productivity if the breaker solution is allowed to invade the formation.

This detrimental effect due to IEM breakers may be explained by various reasons: transport of dissolved filtercake solids,emulsions from mixtures of mud filtrate and breaker and partial trapping of the wetting phase during oil back flow. In our tests no attempt was made to separately quantify the origin of the damage.

Conclusions

The approach developed from SCAL procedures has permitted to improve the standard methodology for experimentally modelling near wellbore fluids invasion, cleanup processes, and to quantify permeability damage. This improved methodology was used to evaluate comparative performances of various drilling fluid formulations and different cleanup procedures which can be applied in open hole wells.

The main limitations of this work stem from i) the nature of the rock samples tested (outcrop sandstones with a low clay content) which limited the potential damage from filtrate invasion and ii) from that our two studies were based only on return permeability measurements without any attempt to quantify separately the impact of the different damaging mechanisms. However the following conclusions can be drawn :

1. Dynamic mud leak off tests on long core samples have allowed to accurately compare spurt losses and stabilised filtration rates for 8 mud formulations.These data are indispensable input parameters to evaluate the depth of filtrate invasion during overbalanced drilling operations.
2. Mud filtration coefficients were always higher for water-based muds than for invert emulsion muds . This means that the depth of invasion, for a given time of mud exposure, will be greater with WBM .
3. Near wellbore permeability impairment was always severe for all mud formulations tested. In the first 5 cm of the wellbore oil return permeabilities were ranging from 8 to 48 % of undamaged initial permeability. Damage beyond this depth strongly depends on the nature and on the composition of the mud. WBM induced an additional damaging effect due to trapping a portion of filtrate during oil backflow . Conversely, Invert emulsion muds may lead to a stimulating effect , i.e. return permeability greater than 100 % at 10-30 cm from wellbore. This suggests that a favourable relative permeability effect due to a reduction of connate water may take place during oil backflow.
4. All WBM breakers tested showed a good efficiency to remediate filtercakes but their reactivity largely vary from one to another. Critical contact time is a relevant parameter to evaluate the soaking time for the breaker to go through the filtercake.
5. The use of a specific cleanup procedure with IEM breakers is not always recommended for wells drilled with an invert emulsion mud since a detrimental effect was observed after breaker invasion. In such a case it is recommended to favour a natural cleanup by oil backflow.
6. Finally, evaluation and remediation of formation damage require to conduct appropriate laboratory tests under carefully controlled conditions representative of the borehole conditions. Special attention must be paid to generate return permeability data at representative oil flow rates (vertical well versus horizontal well). Failure to this point may lead to overestimate or underestimate permeability damage depending on the rate applied in laboratory tests.

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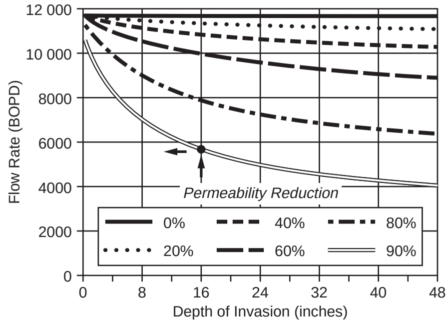

Figure 1: Flow rate impairment due to filtrate invasion for an horizontal well

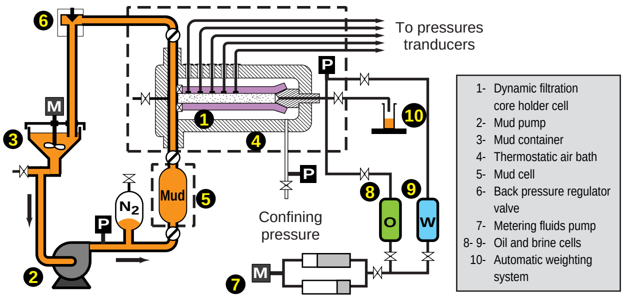

Figure 3: Equipment for dynamic mud leak-off tests on long core samples.

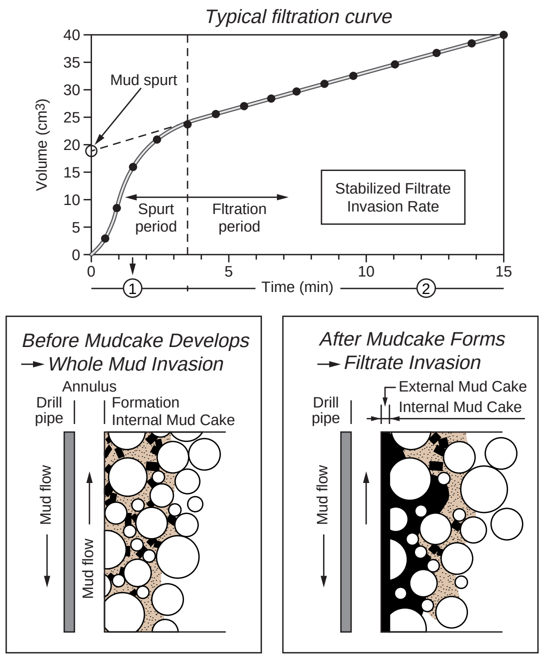

Figure 2: Drilling fluid invasion and filter cake formation.

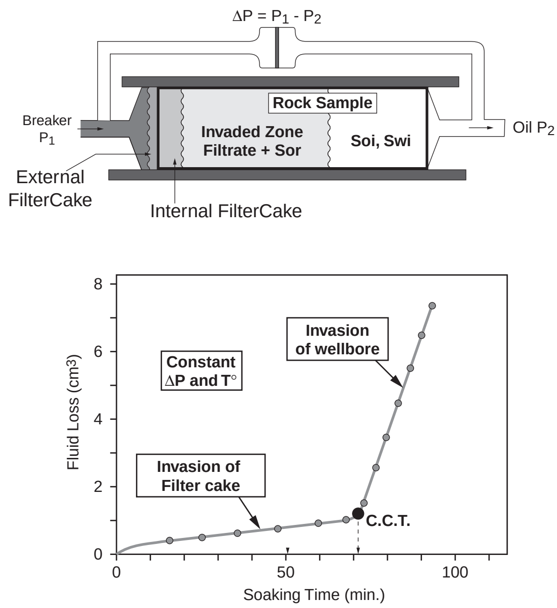

Figure 4: Typical fluid loss curve during breaker treatment.

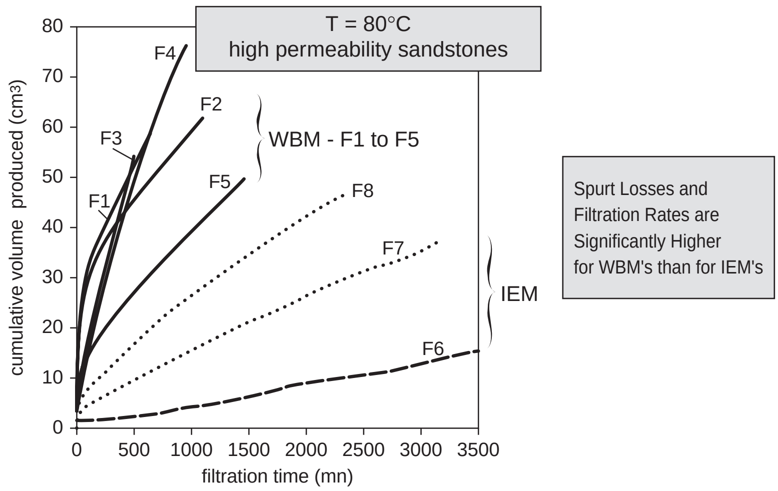

Figure 5: Filtration curves for the 8 muds tested.

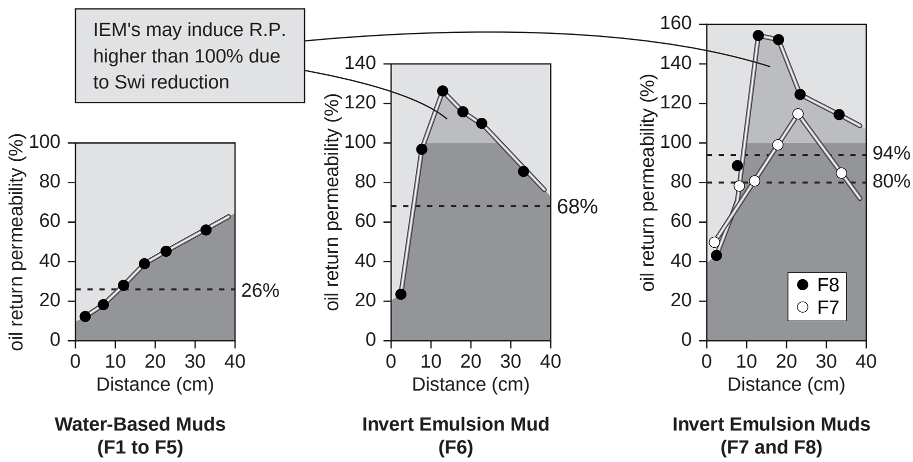

Figure 6: Comparison of return permeabilties – WBM vs IEM.

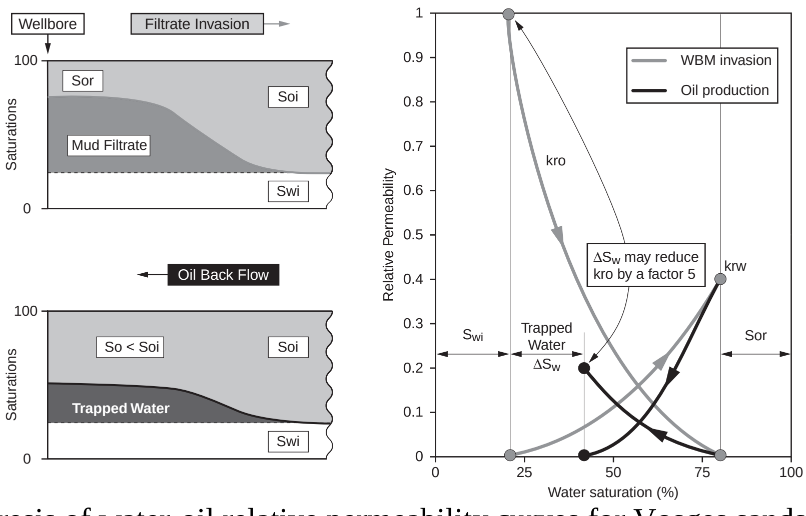

Figure 7: Hysteresis of water-oil relative permeability curves for Vosges sandstone.

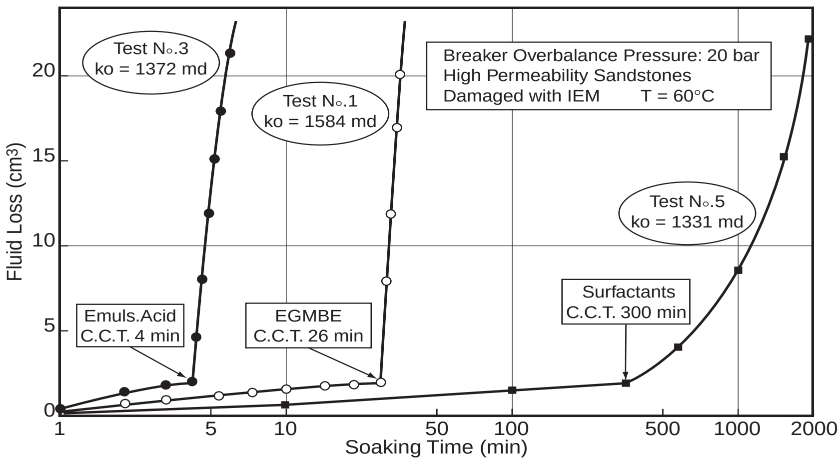

Fig.8 - Fluid loss curves obtained with IEM breakers. Critical Contact Times strongly vary from one to another.

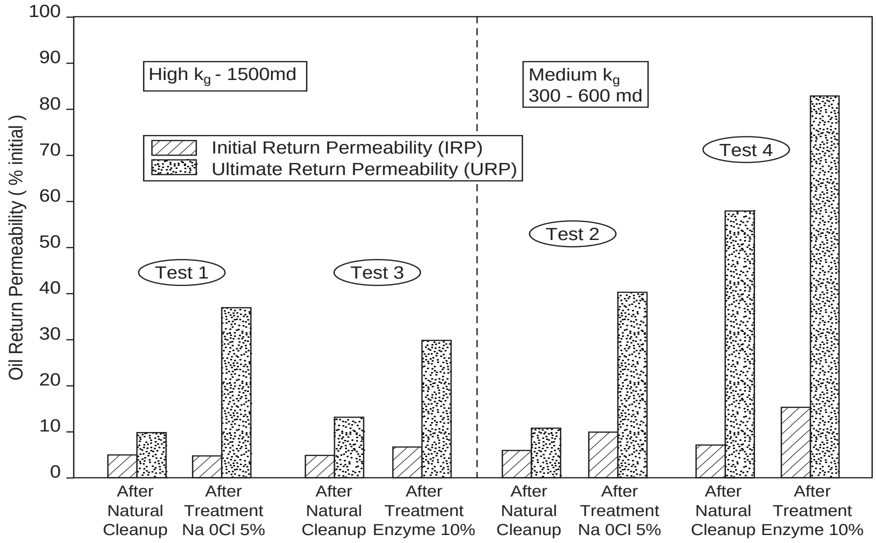

Fig.9 - Comparison of return permeabilities after natural cleanup and after treatment. Cores damaged with water - based mud.

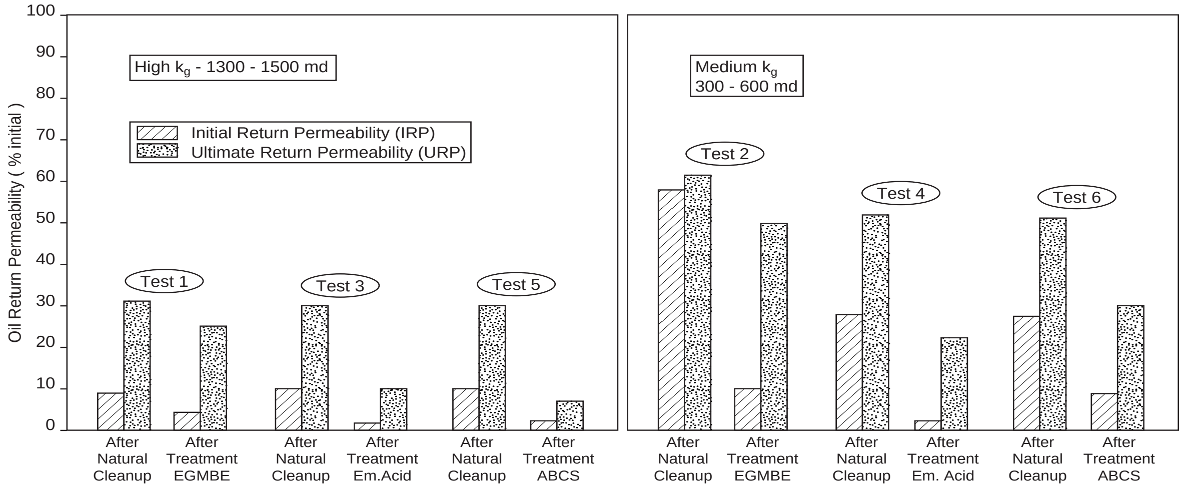

Fig.10 - Comparison of return permeabilities after natural cleanup and after treatment. Cores damaged with invert emulsion mud.