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Effect of overbalance pressure on formation damage

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Abstract

Experiments were conducted to investigate the influence of overbalance pressure on formation damage during drilling operations. An innovative ultrasonic method was employed to measure mud invasion depth. It was observed that mud invasion depth decreases with increasing overbalance pressure until it reaches a critical pressure. Beyond that, invasion depth increases with overbalance pressure. The above phenomenon reflects a strong physical relationship between overbalance pressure and mud fines and filtrate invasion depth.

Keywords: Formation damage; Mud invasion depth; Horizontal wells; Overbalance pressure; Nondestructive evaluation

1. Introduction

The main purpose of drilling vertical or horizontal wells is to produce maximum recoverable oil at minimum cost. Unfortunately, drilled wells are subject to formation damage with varying degree of severity, depending upon the drilling conditions. This is mainly due to the invasion of drilling fluids during drilling operations. The formation impairment or skin due to drilling fluid invasion around the well bore reduces well productivity. This is especially true for wells completed either open hole or with slotted liner due to the difficulty to undertake any stimulation job to alleviate formation damage problems. Nowadays, horizontal wells are preferred over vertical wells because they offer a net productivity enhancement as well as an increase of the contact area with the reservoir. However, formation damage is more critical to horizontal wells because these wells have such long exposed interval that stimulation jobs are not efficient and feasible.

2. Formation damage concepts

Ever since van Everdingen (1953) and Hurst (1953) introduced the concept of a skin factor, the primary focus of research has been on evaluation and minimization of formation impairment. Formation damage may be defined as a process that results in

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a reduction of the flow capacity of an oil-, water-, or gas-bearing formation. The formation can be damaged during drilling, casing and cementing, completion, well servicing, well stimulation and production operations. Drilling operation is considered as the primary initiator of formation impairment as virgin formation comes first time in contact with a foreign fluid, i.e. drilling mud, which invades the formation and plugs the pores around the well bore. Although drilling fluids are presently being designed in such a way to minimize solid and fluid invasion into the formation by building a quick mud cake on the formation face, but it is during the first few seconds that the drilling fluids are in direct contact with formation before the appearance of mud cake that cause major solid and fluid invasion. These early spurt losses occur before mud cakes have a significant contribution in the overall severity of formation impairment. After the early spurt losses, solid particles in drilling fluid start bridging the pores and form a mud cake on the formation face. The mud cake essentially stops the solid invasion and reduces the filtration rate. Even the invading filtrate plays a critical role as it reacts with formation rock and cause clay swelling and dispersion and produce precipitation of salt in the pore, which also reduces formation permeability.

Apparently, the best way to control formation damage is to minimize particle and filtrate invasion by building a fine-quality, low-permeability and high-strength mud cake around the well bore (Di and Sharma, 1992). Such external mud cakes are a function of the average pore size in the formation, median particle size of bridging additive materials and their concentrations (Lynn, 1998; Di and Sharma, 1992; Peden et al., 1984; Krueger, 1986; Rahman and Marx, 1991; Reza and Mazeel-Alaboudi, 1992; Ismail and Arshad, 1994; Shaw and Chee, 1996; Burnett, 1996) as well as drilling operation conditions, i.e. overbalance pressure. In this context, Abrams (1977) recommended a minimum bridging particle concentration of 5% and a ratio of 1:3 between the average pore size and medium particle size, while Yan et al. (1996) reported that the optimal effect of bridging occurred when particle diameter is 1/2–2/3 of pore size. Similarly, in an effort to evaluate the effect of drilling operation conditions on formation damage, Marx and Rahman (1987) showed that differential pressure itself does not lead to severe formation damage but only in the first 2 in. or so of the core section due to invasion of mud particles, whereas Saleh et al. (1997) indicated that more damage occurs in the region of maximum overbalance pressure.

3. Scope of the work

The impact and importance of skin damage on the economical production of crude oil seriously engaged the attention of many researchers in the last five decades. Using physical, analytical and numerical simulation models, it has been proven that oil reservoirs can be damaged in three different ways. *Physically*, the formation can be damaged by (a) the invading mud solids that block the pore channels, (b) the narrowing of capillaries due to adsorption of invaded polymers, and (c) water block, emulsion block and gas block. *Chemically*, the formation can be damaged by the reaction between the filtrate and pore contents and/or matrix materials. Swelling or dispersion of clays and precipitation by the reaction between mud filtrate and the pore contents as well as solution of salts and minerals from the matrix are the main factors. Biologically, the formation can be damaged by colonies of bacteria and their precipitated products can block the pore channels (Bennion et al., 1996). It has been also experimentally proven that water-based muds (WBM), which are usually used in drilling oil and gas wells, impair the formation permeability more significantly than the oil-based muds (OBM) and the polymer-based muds (Porter, 1989; Lynn, 1995, 1998; Ryan et al., 1995; Yan et al., 1996; Longeron et al., 1998). The filtrate generated by WBM is more likely to cause physical and chemical reaction with in situ reservoir fluid and rock, and can induce severe damage. Part of the formation damage may be permanent. Once the mud particles have invaded the rock, it is difficult to remove them by back flow. The severity of formation damage or skin is directly related to the permeability impairment and depth of that impairment around the well bore and it is well understood from the published literature that the skin is a function of overbalance pressure, pore sizes in the formation and particle size distribution in the drilling fluid, formation permeability and the nature of the drilling fluid used.

The objective of the present work is to better understand the influence of overbalance pressure on formation impairment during drilling operations. An innovative ultrasonic method was used to measure the mud invasion depth in order to investigate the relationship between the overbalance pressure and the invasion depth.

A leak-off apparatus was constructed to simulate the mud circulation process across the formation face during drilling operation. Berea sandstone cores that are known for their homogeneity were used. Sample cores of nearly the same effective permeability and pore size distribution are selected to perform experiments in order to eliminate the effect of core permeability and pore size distribution on the present study. These core samples are subjected to different overbalance pressures for various mud contamination times under actual reservoir conditions. All other parameters, like mud composition, confining pressure, pore pressure and temperature, were kept constant. Regain permeabilities and skin factors are calculated using the experimental data obtained from the leak-off apparatus. The mud invasion depth was measured by comparing the ultrasonic wave velocity profiles along the length of the damaged samples to the corresponding velocity profiles for nondamaged cores.

4. Experimental set-up

Leak-off experimental setup is designed to simulate the drilling fluid circulation process at the formation face in the well bore under bottom hole conditions.

4.1. Apparatus

A Hassler type core holder (Fig. 1) was used in the experiment. This stainless steel core holder can accommodate up to 30.48-cm-long and 5.08-cm-diameter cores. The core is mounted inside the rubber sleeve and subjected to overburden (confining) pressure. One end piece of the core holder was fabricated to have two ports and referred to as ‘injection end’. These ports were used to circulate the drilling fluids across the face of the core and also to inject oil and brine as well. The other end piece, known as ‘production end’, had only one port to collect the filtrate/oil/brine, pumped from the injection end (Gruber and Adair, 1995).

A stainless steel spacer 1 cm in length was placed between the core face and the injection end to allow the mud to circulate and form cake on the core face. Transfer cells were employed to deliver mud/oil/brine to the core holder. A Beckmann piston pump was connected to the transfer cell to deliver the fluids (mud/

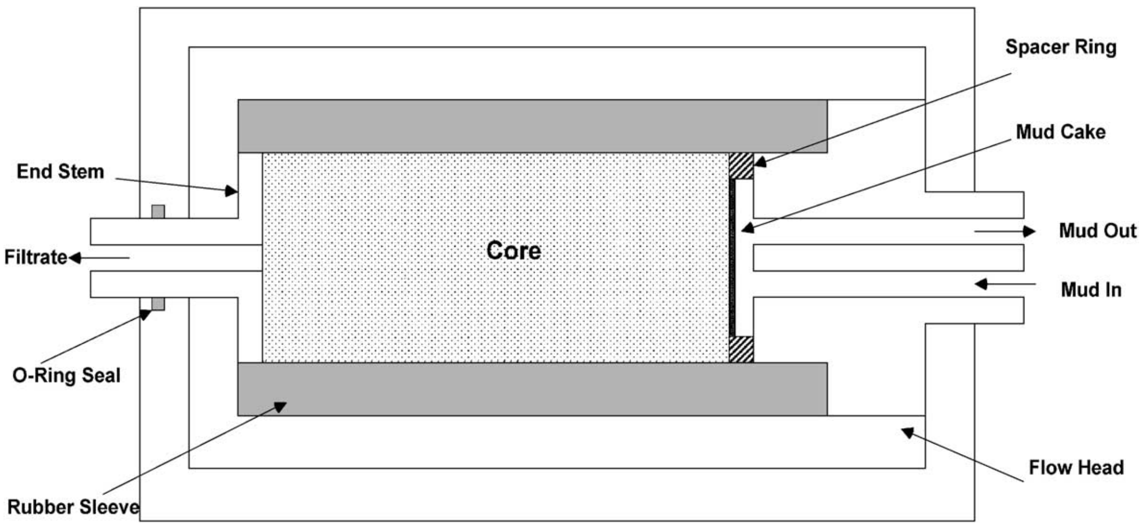

Fig. 1. Hassler type core holder.

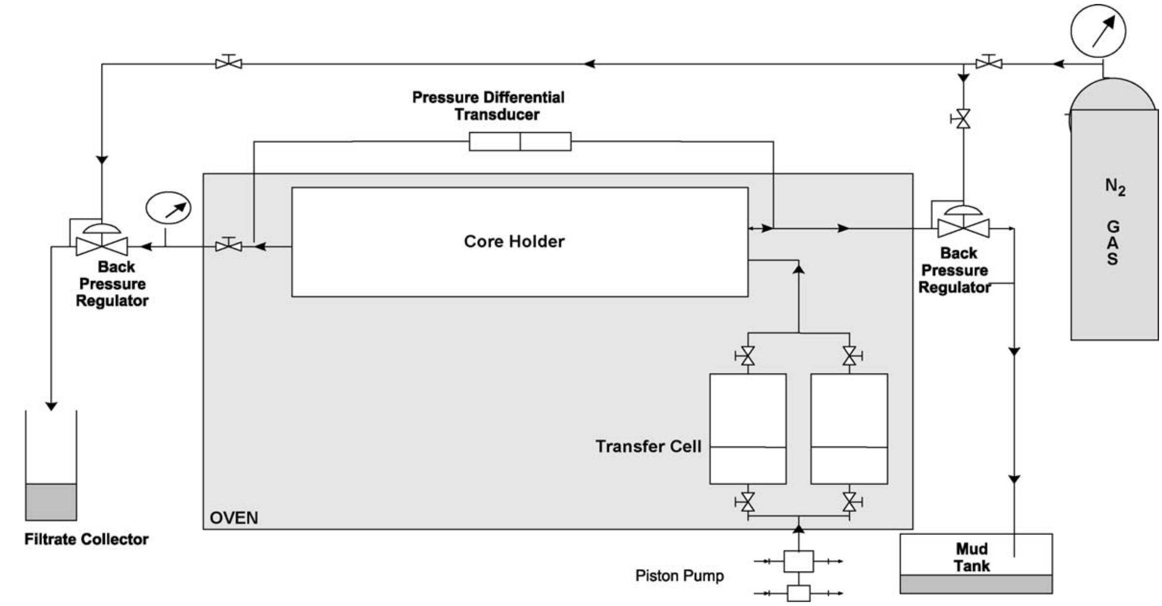

Fig. 2. Schematic of leak-off apparatus.

oil/brine) at desired flow rate and pressure. A mixture of kerosene and silicon oil is used as transferring fluid in the pump. The pump could deliver the fluid at a maximum flow rate of 10 cm^3/min and pressure of 10,000 psi. Back pressure regulators (BPR), at each end, were installed to control and maintain the desired pressure in the system by mean of pressurized nitrogen gas. A regulator at the injection end was used to maintain the overbalance pressure across the core, while another one retained the pore pressure inside the core. A Validyne DP303 differential pressure transducer was mounted over the core holder for measurement of differential pressures across the core. These differential pressures are displayed on analogical digitor. The electrical signals sent by the transducer were also transferred to a chart recorder where pressure difference across the core was recorded.

An ISCO fraction collector was used to collect the produced fluids in 10 cm^3 test tubes. The fraction collector could be set to rotate with time. In this way, the volume collected in a certain time could be recorded. The whole setup, except for the pump and the backpressure regulators, was confined in an electric oven to operate at reservoir temperatures up to 300 j C. A schematic diagram of the leak-off apparatus is shown in Fig. 2.

4.2. Pre-experimental procedures

4.2.1. Fluid preparation

A 33.5j API Arabian medium crude oil was used in the experiments. Paraffinic compounds were removed using a 1-Am oil filter. A 3.5% (35,000 ppm) KCl brine was prepared to saturate the cores. A 35 g KCl is dissolved in 1 l of distilled water in a stirrer for 1–2 h. Brine was then filtered by no. 50 filter paper and evacuated in a desiccator to remove air bubbles for 1–2 h. This brine was selected to avoid clay swelling and clay migration and to keep the salt

Table 1
Composition of water-based polymeric drilling fluid

	Composition per liter
Water, cm^3	1096
KCl, g	133
XC-polymer, g (Xanthan Gum) (thickener and suspending agent)	5.0
Disprac, g (filtration control agent)	1.7
Dextrid, g (filtration control agent)	20
KOH, g	1.0
$CaCO_3$ (fine), g	16.7

Table 2
Properties of water-based polymeric drilling fluid

	Values
Density, ppg	9.1
Fluid loss, per 30 min, ml	6.7
pH	9.77
Apparent viscosity, cp	31.5
Plastic viscosity, cp	19.0
Yield point, cp	25
Gel strength (10 s), lb/100 ft^2	5.5
Gel strength (10 min), lb/100 ft^2	6.0
Power law index, *n*	0.577

concentration above the critical salt concentration. A water-based polymeric drilling fluid was used during the experiments. The composition and properties of the drilling fluid are given in Tables 1 and 2, respectively. An image analyzer was employed to measure the particle size distributions, shown in Fig. 3.

4.2.2. Core preparation

Berea sandstone cores are reduced to required size. Their dry weights, dimensions, gas porosities and gas permeabilities are determined. Then cores are evacuated for 8 h in a saturator before leaving them to soak in brine for 12 h under 2500-psi pressure as per API recommended procedure (API Recommendation Practice for Core Analysis, 1998). Gas porosity and permeability and pore size distributions of Berea sandstone were determined for each sample before running the leak-off test.

4.2.3. Core selection

Sample cores of nearly the same effective permeability 450 F 120 md to crude oil and pore size distribution are selected. Pore size distributions of some core samples measured by centrifuge method are shown in Fig. 4.

5. Experimental procedure

The experimental procedures for leak-off test consisted of the following steps.

5.1. Absolute permeability

Brine was used to determine the absolute permeability of core under reservoir conditions. Fully brine-saturated Berea cores are mounted inside the core holder and flooded with brine at a constant flow rate until steady state was achieved. Differential pressures at different flow rates were measured by means of pressure transducer. The absolute permeability was determined by using differential pressures and flow rates through regression analysis and Darcy's equation.

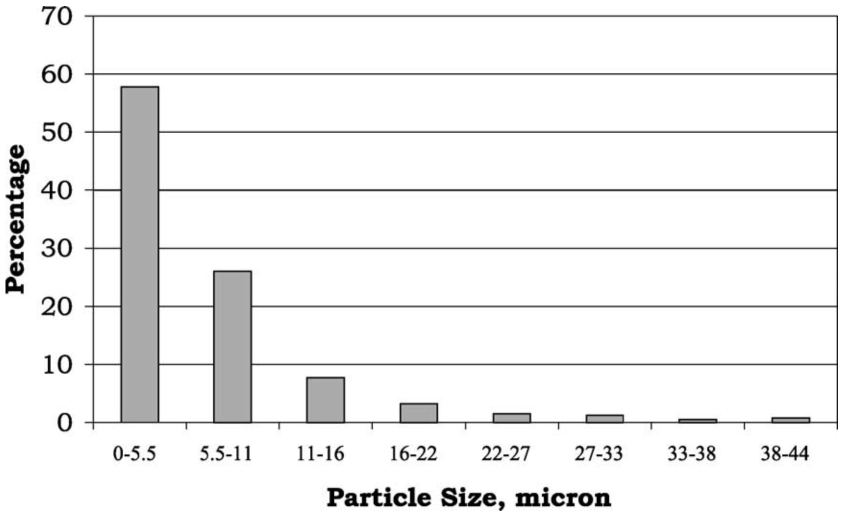

Fig. 3. Size distribution of bridging particles by image analyzer.

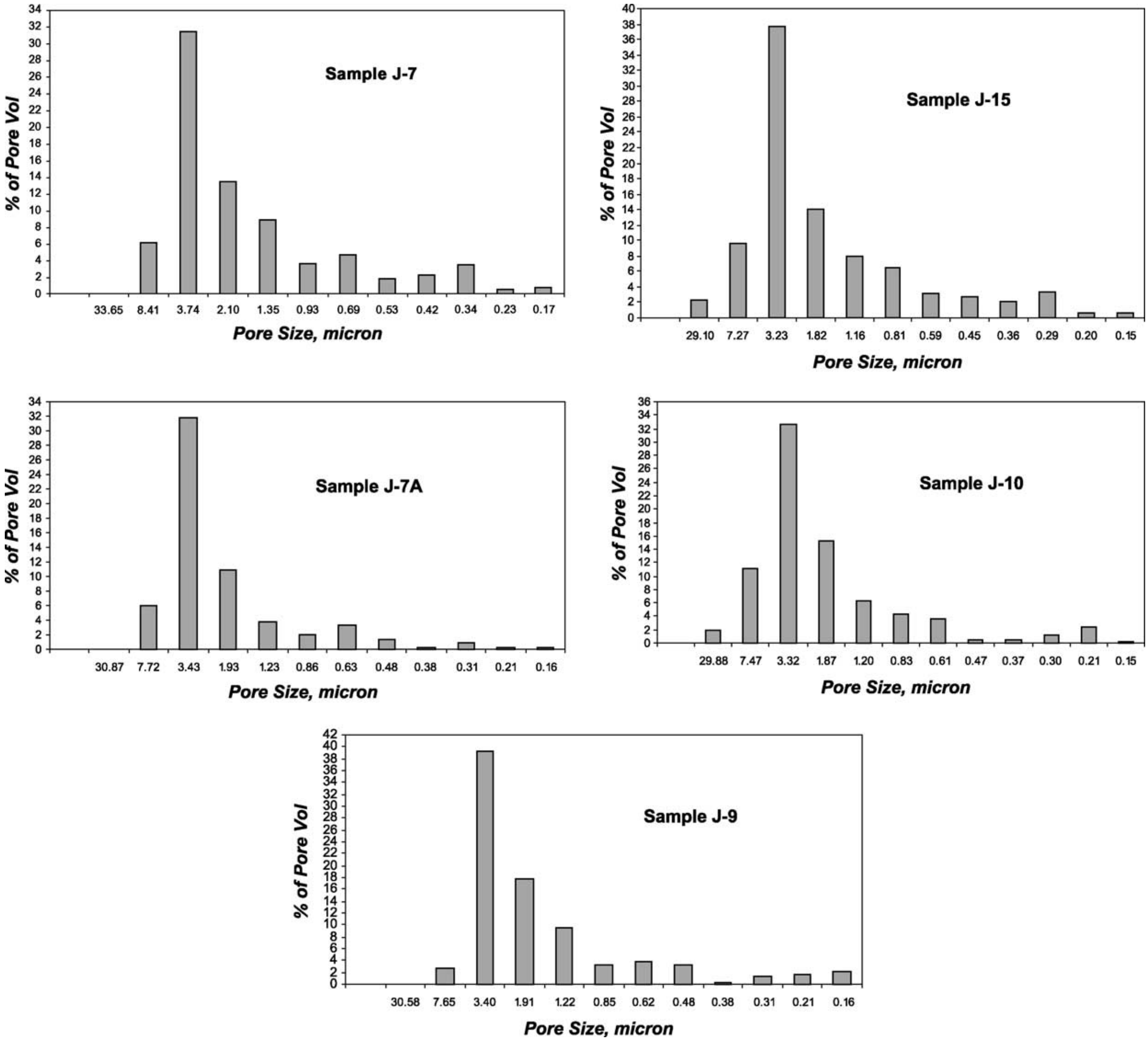

Fig. 4. Pore size distribution for Berea core samples.

5.2. Sw_i and effective permeability

After flooding with brine, filtered crude oil was passed through the core at a very slow rate to displace brine in order to get irreducible water saturation Sw_i. Initially, five pore volumes of displaced oil and brine was collected in a graduated flask to get Sw_i by phase separation overnight. Oil permeability was also measured by flowing crude oil through the core and measuring the flow rates and differential pressures under steady state conditions. This effective oil permeability is considered as initial core permeability before damage or mud circulation.

5.3. Mud circulation

Drilling fluid was circulated across the saturated core at a constant flow rate of 1.0 cm^3/min under different overbalance pressures. A backpressure regulator installed at the drilling fluid outlet was used for this purpose. Fresh mud was provided to the core through the transfer cell and collected in a tank at the

Table 3
Experimental measured values for leak-off tests

	DP = 100 psi				DP = 200 psi	DP = 300 psi			DP = 700 psi		
	J-12	J-15	J-14	J-16	J-17	J-13	J-7	J-7A	J-8	J-9	J-10
Diameter, cm	5.01	5.03	5.03	5.03	5.04	5.02	5.10	5.10	5.11	5.12	5.08
Length, cm	10.11	20.25	25.40	25.40	20.70	9.74	10.45	10.56	10.33	10.14	10.37
Cross sectional area, cm^2	19.70	19.87	19.82	19.82	19.94	19.74	20.42	20.42	20.50	20.54	20.26
Porosity, %	21.23	21.78	21.47	21.47	21.72	21.82	21.68	20.49	21.61	20.83	21.30
Pore volume, cm^3	42.29	87.70	108.10	110.12	89.70	41.96	44.84	44.20	45.79	43.40	44.75
Sw_i, %	27.86	27.02	26.04	31.90	27.53	25.52	28.63	26.50	26.84	26.26	29.61
Absolute permeability, md	438	492	440	623	591	531	383	–	461	481	503
Mud damage data											
Mud circulation period, h	4	12	24	48	24	4	12	24	4	12	24
Effective permeability (before mud)	350	444	332	571	463	380	340	387	330	375	388
Effective permeability (after mud)	303	373	251	201	267	306	232	126	138	106	101
Regain permeability, %	86.6	83.9	75.6	35.2	57.7	80.6	68.2	32.6	41.8	28.3	26.0
Invasion depth, cm	7.8	9.7	12.9	16	9.75	6.34	7.95	8.31	6.83	9.24	11.97

outlet end of the core continuously. As the circulation starts, a mud cake begins to form on the face of the core and the filtrate also starts invading the core. As the invading filtrate pushed the oil, the effluent was collected from the production end in a fraction collector at desired time intervals. The filtrate had to pass through a 1000-psi backpressure regulator before accumulating in the fraction collector. The drilling fluid is circulated for different time periods and at different overbalance pressures. At this point, the core was assumed to be damaged with invaded filtrates and mud particles.

5.4. Return oil permeability

The permeability of the damaged core was determined by flowing the oil in the opposite direction at constant flow rate until steady state was achieved. This oil permeability was referred to as return oil permeability after the damage. The values measured are presented in Table 3.

5.5. Method of measuring the invasion depth

The experimental setup for ultrasonic measurement of invasion depth consisted of two panametric transducers used to launch and receive longitudinal waves using panametric pulser-receiver. The transmitted signals were amplified by a panametric preamplifier and recorder on 500 MHz digital oscilloscope and a personal computer. Cylinder-shaped rock samples were investigated by sending ultrasonic waves along the diameter at different position scanning the entire length with a 0.5-cm resolution. The transit times of the waves traveling from the source to the receiver at different positions along the length were stored in the computer. Velocities of the longitudinal ultrasonic waves were determined simply by calculating the ratios of the specimen thickness (i.e. diameter) and the transmit times. For each sample, the wave velocities were measured under three different conditions, i.e. dry, oil saturated (So_i and Sw_i) and mud invaded.

6. Experimental results

Parameters like regain permeability, mud invasion depth and skin were obtained for each core sample. Comparisons were made in order to evaluate the impact of overbalance pressure on the formation

Table 4
Constant parameters for leak-off tests

Constant parameters	Values
Temperature, j F	150
Confining pressure, psi	2500
Pore pressure, psi	1000
Differential pressure, psi	1500
Mud flow rate, cm^3/min	1.0
Mud compositions	constant

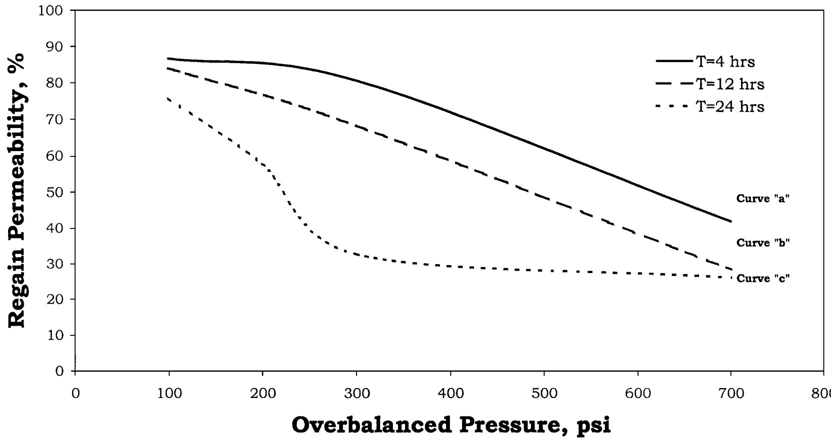

Fig. 5. Effect of overbalance pressure on regain permeability at different contamination times.

impairment while keeping all other parameters constant. In particular, the temperature of the sample, confining pressure, pore pressure, differential pressure, mudflow rate and mud composition were kept constant during all the reported experiments. Their values are presented in Table 4.

6.1. Effect of overbalance pressure on regain permeability

Experiments were carried out using four different overbalance pressures, DP values of 100, 200, 300, 700 psi. The effect of DP on the regain permeability, which is defined as mud damage permeability divided by initial permeability, is evaluated for different mud circulation times. A general trend exhibiting a decreasing regain permeability with increasing DP is observed, as shown in Fig. 5. Curve "c" in Fig. 5 illustrates the regain permeability for different DP maintained for 24 h during mud circulation. Decreases in regain permeability of 75.6%, 57.7%, 32.6% and 26% were observed at DP of 100, 200, 300, and 700 psi, respectively. One possible reason for this decrease is that, with the increase in DP, more force acts on the mud solid particles to enter into pores while circulating across the formation. As the consequence, the large sized particles in the drilling fluid (>1/3 of pore size) start sticking firmly to the pore throats, thereby blocking or constricting the pore throats more firmly. During back-

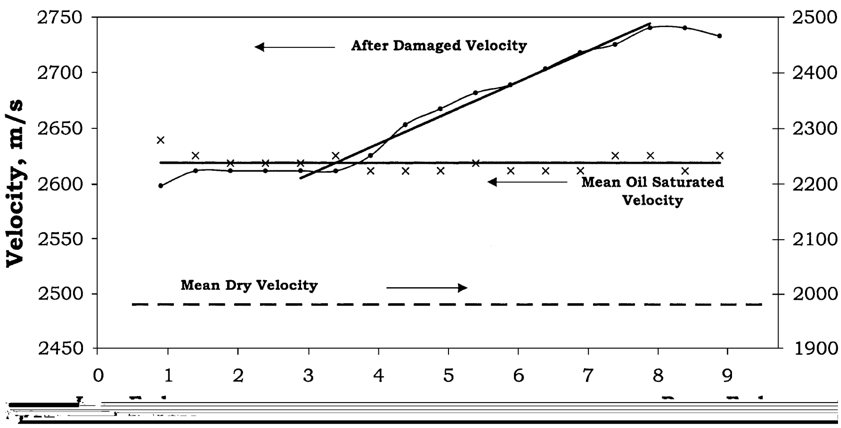

Fig. 6. Ultrasonic velocity profile for core sample under DP = 300 psi, maintained for 4 h.