FORMATION DAMAGE IN A SIMULATED LOWER CRUSE FORMATION*

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Summary

A piston loaded test cell was used to study the effects of fines migration in the Lower Cruse Formation. The sand pack was prepared from an outcrop of the Lower Cruse Formation. The clays identified in this formation were illite/montmorillonite and kaolinite. The effect of migrating clays and quartz fines was studied by a sequential flow displacement of the brine (Na Cl) saturated pack with chloride solutions of sodium, calcium and potassium (25000 ppm). Backflooding of the sand pack with 2 pore volumes of fluid restored the permeability to its original value. The effect of swelling clays was investigated by flooding the pack with fresh water resulting in a permeability loss which was only partially restored with chloride solutions.

INTRODUCTION

Formation damage in unconsolidated sandstone reservoirs poses a threat to the economic recovery of hydrocarbon reserves and is a result of the following factors:

(i) migration of fine particles through the porous reservoir matrix
(ii) swelling of indigenous clay particles.

Fine particles are present in unconsolidated sandstone reservoirs and are not held in the overall cement matrix that bind the larger sand grains but are loosely attached to the outer surface of the grains. These particles include clays and other minerals and are classified here as those passing through a #300 British mesh screen($< 53\mu m$). They are free to migrate with the fluids flowing in the reservoir and cause plugging at pore throats and pore restrictions. The other form of pore plugging is the result of swelling of water sensitive clays (montmorillonite and mixed layer clays) when exposed to fresh water. The plugging of pore throats leads to a reduction in reservoir permeability and extreme productivity decline.

This paper describes the design and operation of a piston loaded test cell to conduct flow studies. The cell is an adaptation of the design presented by Coulter et al[1]. Flow tests conducted with a simulated Lower Cruse sand pack at different overburden pressures and a sequence of different fluids showed that formation damage was caused by movement of fine particles and swelling of water sensitive clays. Qualitative X-ray analyses showed the presence of montmorillonite/illite and Kaolinite in the sand used in these flow tests. Formation damage caused by particle movement was a slow process which could be reversed by backflooding the core. Formation damage caused by clay swelling was almost instantaneous and was prevented by maintaining small concentrations of monovalent or divalent chloride salts in the injected fluids. The salt solutions were not effective in restoring bed permeability after clay swelling had occurred.

Attempts were made to distinguish between fines migration and clay swelling damage using graphical plots of core permeability against pore volume throughput.

LITERATURE SURVEY

Flow studies by Muecke[2] showed that unconsolidated sandstone reservoirs contained large quantities of fines

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of varying chemical composition. His observation indicated that the wettability of the particles and the flow velocity of the wetting phase controlled the movement of these particles.

Gray and Rex[3] utilised X-ray diffraction and electron microscopy to show that mobile clays, needle-shaped mica and hexagonal shaped kaolinite existed as authigenic crystals on the pore walls and were dislodged by changes in water chemistry together with water movement. These crystals were trapped at pore throats where an internal filter cake developed and resulted in permeability loss. Gruesbeck and Collins[4] developed a parallel-pathway model to prove that the minimum interstitial fluid velocity for fines entrainment depended on the properties of both the porous medium and the contained fluids. Their flow studies also showed that fines entrainment and deposition could cause abnormal productivity decline and that entrained fines were not restricted to clay minerals.

Neasham[5] used scanning electron microscopy (SEM) to show that clay particles occur in pores as:

(i) Discrete (not intergrown) particles
(ii) Intergrown crystal linings on pore walls
(iii) Crystals bridging across pores

The different clay morphologies significantly affect the flow properties of the porous medium. Jones[6] showed that small concentrations of calcium or magnesium in formation and invading waters could effectively restrain clay blocking. This behaviour depended on the cation exchange properties of the clays. Clays having adequately absorbed calcium or magnesium restricted dispersion by water and prevented permeability decline. Abrupt change from high saline to fresh water could also cause clay blocking which could be inhibited if the water salinity is lowered gradually.

Sand control during field operations is a chronic and expensive problem to eliminate. Studies by Gulati and Maly[7] and Saucier[8] recommended a gravel to sand ratio of less than 6 for effective sand bridging. Maly and Krueger[9] stressed the need for proper sand sampling prior to gravel selection. Durrett et al[10] while initiating an extensive sand control study, observed that loose packing of gravel created voids in the pack and subsequent settling which would render the sand control attempt ineffective. Holman[11] and Likwartz[12] presented extensive studies of sand control in the offshore Amoco Teak field (Trinidad). These studies reiterated the need for complete understanding of all field parameters before any costly attempts were made to resolve the problem.

Mower and Soverall[13] while conducting a field study of the Teak field sand problem stressed the need for ultimate depletion mechanisms in laboratory tests. Previous studies on sand control in that area had not extended the tests to include water production and the ineffectiveness of coarser gravels under conditions of high water cuts went undetected. Their observation that the incidence of water aggravated sand production was in close agreement with Muecke's theory of dependence of particle migration on particle wettability and flow velocity of the wetting phase.

All the aforementioned studies show the adverse effect of particle migration and clay swelling, that fines migration and production precede sand production and that determining the parameters controlling fines migration is a positive step towards resolving the sand production problem.

APPARATUS

A schematic of the apparatus used to conduct flow studies is shown in Fig. 1 and consisted of the following:

(i) Piston loaded test cell
(ii) Feed pump and flow dampener
(iii) Hydraulic system for piston loading

The piston loaded test cell (PLTC) was an adaptation of the design presented by Coulter et al[1]. The cell consisted of a 10.4 cm (4.1 in) internal diameter thick walled cylindrical steel pipe 75.7 cm (29.8 in) in length which served as a core holder. Each piston had a diameter of 10.3 cm (4.1 in) and length of 5.5 cm (2.2 in). A hollow shaft 53.1 cm (20.9 in) in length traversed the central axis of each piston (Fig. 2).

The sand was compressed between the piston at either end of the cell. The inner wall of the core holder was highly polished to allow easy movement of the piston. The overburden pressure was applied behind the pistons and was completely isolated from the sand pack and atmosphere by utilising the following:

(i) O-rings on the circumference of the pistons
(ii) O-rings at the centre of the outer flange through which the hollow piston shaft passes.

The hollow cylindrical piston shafts extended through the outer flanges and served as the flow path for the test fluids. The design allowed the feed to be pumped into the shaft and onto the sand pack without being exposed to the overburden pressure region. Fluid injected into the piston shaft traversed the core and left at the extreme end of the other piston shaft.

The entire core holder was mounted on a frame which facilitated its rotation to a horizontal or vertical position.

Feed was provided at constant flow rate by a Model MA motor driven positive displacement chemical pump.

The reciprocating action of the piston caused pressure surges and pulsating feed injection rates. This was eliminated by passing the feed through a cylindrical flow dampener. An air pocket in the dampener absorbed the shock of pressure surges and allowed steady fluid injection rates.

Overburden pressures were obtained with a TK Simplex Fine Charger rotary pump. The pressure was applied to the back faces of the pistons by pumping of hydraulic fluid through connections in the outer flanger (Fig. 2). This served to compress the sand pack at the confining pressure required.

All flow lines were of 0.64 cm (¼ in) copper tubing. USG pressure guages were used to record pressure data.

The entire apparatus was pressure tested to 6895 k Pa (1000 psi) before flow tests were commenced.

EXPERIMENTAL PROCEDURE

Flow tests were conducted to investigate formation damage in the Lower Cruse sand formation.

RESERVOIR SIMULATION

An outcrop of the Lower Cruse formation was located and separated into various size fractions using the sieve and shaker method. The size distribution analysis curve characterising the sand investigated was utilized in obtaining the percentage of each fraction for batch mixing (Fig. 3). It was assumed that the outcrop sand satisfied the mineralogical content of the reservoir sand.

The compression of the sand core between the hydraulically activated pistons simulated the overburden pressure at the corresponding reservoir depth.

Fluids with properties similar to those found in the reservoir were injected through the sand core.

These procedures were necessary for complete simulation of underground conditions.

PACKING AND FLOW PROCEDURES

The empty core holder was cleaned and rotated to a vertical position. The lower piston, with the outer end of the shaft sealed, was inserted into the cell. The pack material was added in the presence of formation fluid (brine) to exclude air bubbles. When the sand was being added, the fluid level was maintained just above the sand surface to prevent gravity settling of the sand particles. After the bed material was added, the bed was agitated with a long plastic probe to remove trapped air bubbles.

Wire mesh screens were used at either end of the core to obtain an evenly distributed flow regime. Glass wool was used at the inlet end of the core to prevent fine particles from passing through the wire mesh screen and plugging the inlet piston shaft.

The outlet piston was then inserted and the core holder rotated to a horizontal position. The pack was compressed for a 24 hour period before flow tests were commenced. This allowed for the establishment of an even stress field in the core and ensured uniform pressure distribution.

If extreme care were taken during the packing phase to eliminate air bubbles, the capillary forces in the sand had prevented gravity flow of the contained fluids.

The feed pump was started and readings of inlet pressure, fluid flow rate and sediment concentration in the effluent were recorded.

The fluids injected into the sand core included fresh water and chloride solutions of magnesium, calcium, potassium and sodium.

RESULTS

Qualitative X-ray diffraction analysis of the clay fraction of the sand used in the flow tests showed the presence of the following minerals:

(1) Montmorillonite/illite
(2) Kaolinite
(3) Quartz

Fig. 4 shows the plot of core permeability as a function of cumulative pore volume throughput of fluids injected for a sequence of different fluids whose concentrations were 25000 ppm of dissolved solids.

The bed was initially packed under brine (NaCl). The different types of fluids were used to demonstrate formation damage caused by fines migration and plugging and clay swelling.

The initial bed permeability for NaCl solution injection was 15.6 md. This value decreased with increasing pore volume throughput irrespective of the solution type injected, as indicated for chloride solutions of sodium and calcium (Fig. 4 — Points 1-5). After injection of 16 pore volumes (P.V.) of fluid, the bed permeability stabilised at a value of 2.7 md which corresponded to an 83 percent reduction from its initial value.

Backflushing the bed restored 99 percent of the initial core permeability (Fig. 4 — Points 5-6). Continuous chloride solution injection (8 P.V.) was again accompanied by a 60 percent permeability decline (Fig. 4 — Points 6-8) from its initial value. Both fluid injection sequences, (Points 1-5) and (Points 6-8), demonstrate similar permeability decline curve characteristics.

A rapid permeability decline was recorded when 1 PV of fresh water caused a 38 percent drop in permeability (Fig. 4 — Points 8-9) to a 0.3 md value.

Chloride solution (KC1) injection had negligible effect on permeability restoration (Fig. 4 — Points 9-10). Backflooding again restored the bed permeability to 20 percent of its initial value (Fig. 4 — Points 10-11), which corresponded to an increase in pack permeability from 0.6 md to 3.2 md. Continuous chloride solution (KC1) injection again resulted in a gradual permeability decline (Fig. 4 — Points 11-12).

DISCUSSION OF RESULTS

Reduction in bed permeability during the injection of non-damaging fluids (chloride solutions) was caused by migration and plugging of fines in the porous matrix as indicated by the presence of fines in the effluent. The fine particles were entrained in the fluid flowing through the sand pack and were trapped in pore throats or pore restrictions with dimensions small enough to create a physical barrier to particle flow. This plugging resulted in a gradual decline in pack permeability.

After backflushing, the initial permeability was restored. This suggested that all the plugged fines were dislodged from the pore restrictions. Continuous fluid injection again initiated the migration and plugging processes.

The rapid permeability decline accompanying the injection of 1 PV of fresh water suggests permeability damage by clay swelling and chloride solution injection had negligible effect on permeability restoration.

Backflooding again dislodged plugged fines but the bed permeability was restored to only 20 percent of its original value because the swollen clay particles obstructed fluid movement through the sand bed, irrespective of the direction of fluid flow. KC1 solution injection caused gradual permeability decline resulting from fines migration and plugging.

The method of distinguishing between formation damage caused by either migrating clays or swelling clays by referring to the slope of the permeability/pore volume throughput curves was suggested by Gray and Rex[3].

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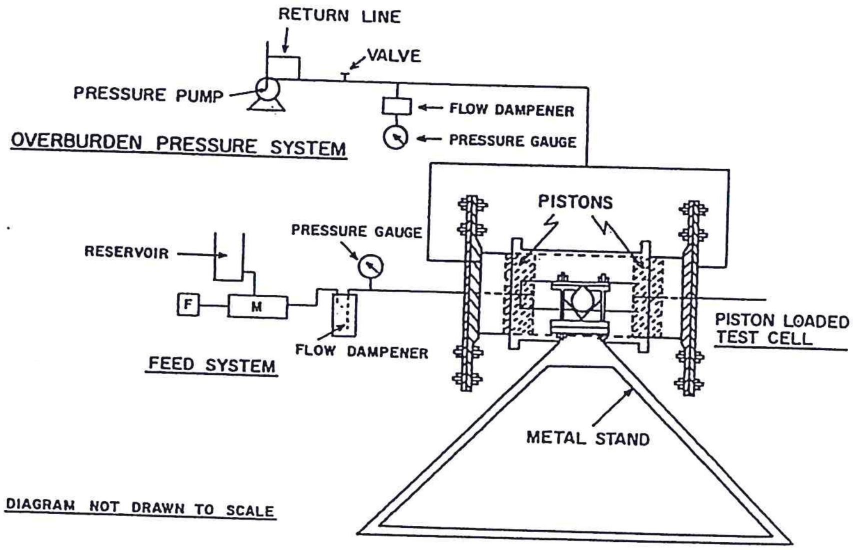
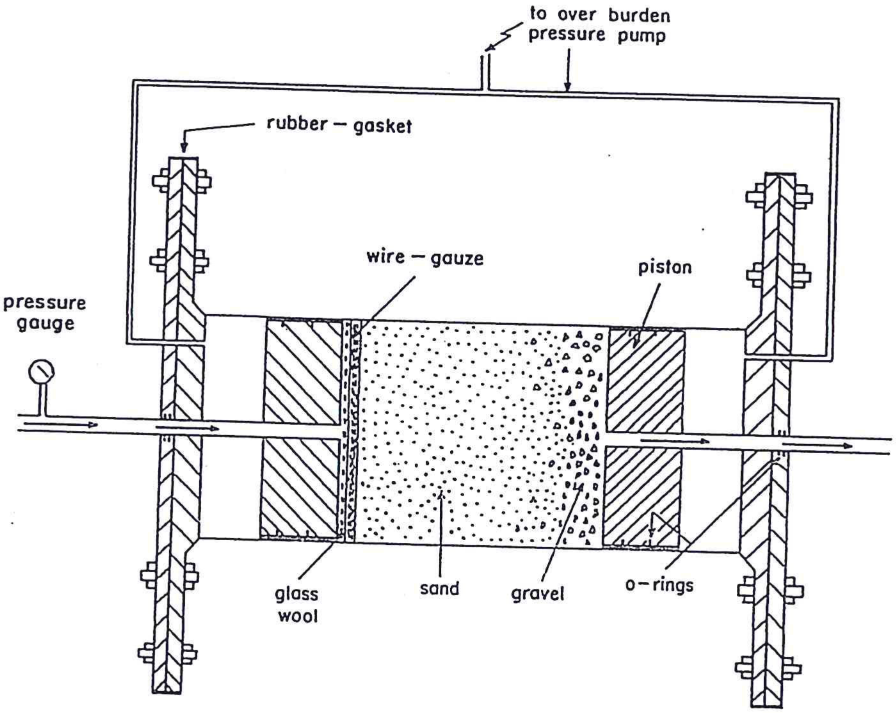


Flow Apparatus to investigate fines migration in sandstone reservoirs

FIGURE 1



Section through apparatus

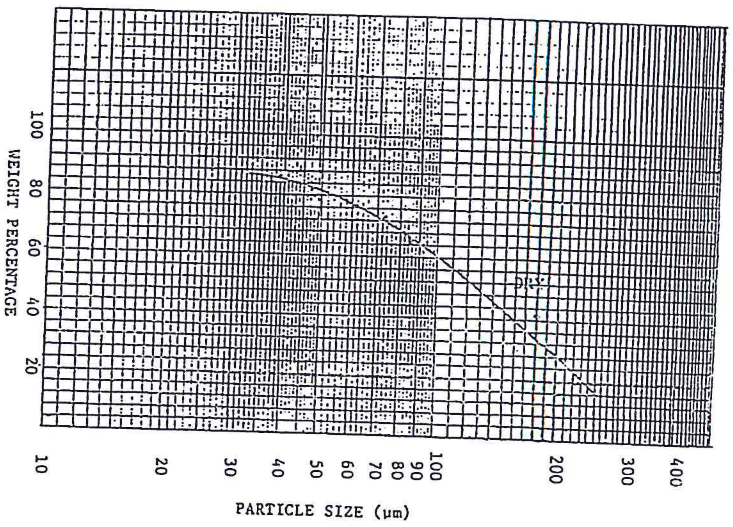
FIGURE 2

SWC DRY
SAMPLE DEPTH - 6275.00B
ORIGINAL WT. - 5.57 GMS FINAL WT. - 5.37 GMS

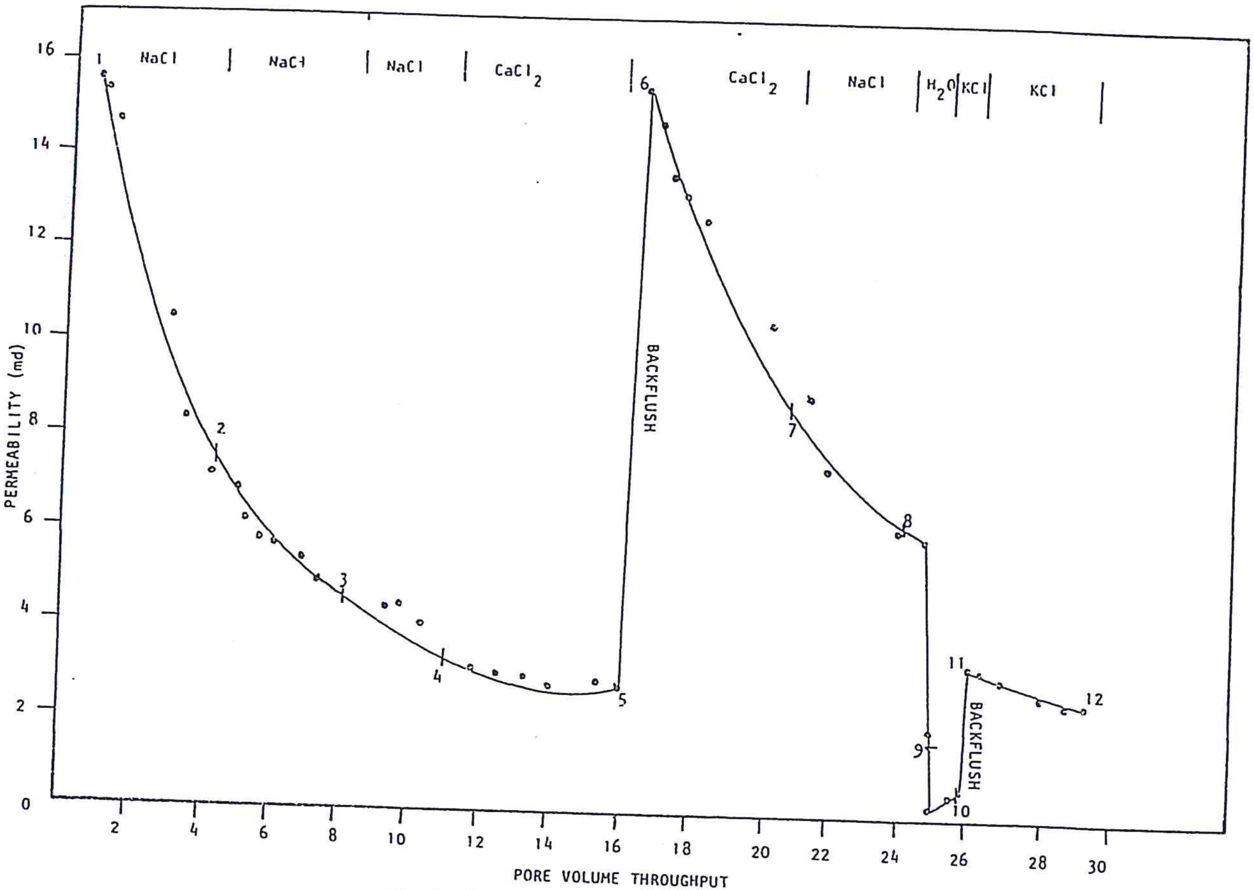
ASTM MESH	APERTURE INCHES	FRAC. WT.	*PERCENTAGE FRAC.	CUM.
45	0.0138	0.00	0.0	0.0
60	0.0098	0.95	17.7	17.7
80	0.0070	1.34	25.0	42.7
120	0.0049	0.74	13.8	56.5
170	0.0035	0.46	8.6	65.1
230	0.0024	0.57	9.7	74.8
325	0.0017	0.38	7.1	81.9
400	0.0015	0.20	3.7	85.6
PASS	0.0000	0.76	14.4	100.0
TOTALS		5.37	100.0	

SWC WET
SAMPLE DEPTH - 6275.00B
ORIGINAL WT. - 5.37 GMS FINAL WT. - 5.37 GMS

ASTM MESH	APERTURE INCHES	FRAC. WT.	*PERCENTAGES* FRAC.	CUM.
45	0.0138	0.00	0.0	0.0
60	0.0098	0.15	2.8	2.8
80	0.0079	0.57	9.7	12.5
120	0.0049	0.98	18.3	30.8
170	0.0035	0.64	11.9	42.7
230	0.0024	0.82	15.9	58.0
325	0.0017	0.46	8.6	66.6
400	0.0015	0.26	4.8	71.4
PASS	0.0000	1.54	28.6	100.0
TOTALS		5.37	100.0	



Sieve Analysis graph sheet
FIGURE 3



Graph of permeability vs pore volume throughput
FIGURE 4