EVALUATION OF FORMATION DAMAGE CAUSED BY DRILLING FLUID IN DEVIATED WELLBORE

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ABSTRACT

Wellbore damage shape around inclined and horizontal wells are commonly assumed as radial. This is a conceptual assumption. A more realistic model was investigated experimentally in this study, since the distribution of damage surrounding an inclined or horizontal well that determines its shapes are not only influenced by the anisotropy of formation rocks but are also strongly influenced by borehole angles and the dynamic of filtration process in drilling. A novel, state-of-the-art engineering core flow tests set up was constructed using long cores which permit in-situ determination of permeability profile as a function of core length. Results from these tests on 5 core sample locations around an inclined wellbore shows that the severity of damage is reduced slightly from the upper side to the lower side around the inclined wellbore wall. Analysis on degree of damage permeability distribution around the inclined wellbore indicated that the damage shape is elliptical.

INTRODUCTION

Formation damage is a very expensive problem to the oil and gas industry. Before the drill bit penetrate a reservoir, the reservoir rock and its constituent minerals and resident fluids are essentially in a state of physico- chemical and thermodynamic equilibrium. This equilibrium is disturbed during the drilling process when extraneous mud solids and fluids are introduced into the wellbore giving rise to pressures in excess of the reservoir pore pressure. The resultant differential pressure, usually referred to as overbalance pressure, promotes the invasion of fine colloidal materials and filtrates into the near wellbore region of the formation where they reduce the intrinsic permeability. This impairment is commonly refered to as formation damage or skin damage.

Formation damage can be caused by either a simple or complex process and occurred naturally or self-induced by the well throughout the well operation from drilling and completion to production to workover. The dynamics of the drilling process alone is so great that it has to alter adversely the rock's ability to flow fluids. It has been shown that of the total filtrate invasion that take place during drilling, about 80% is due to dynamic filtration mechanism[1]. Early core studies indicated that

formation damage could be controlled most efficiently with oil-based muds or with water based muds that contain divalent ions[2,9], such as Ca^{++} and Mg^{++}. Although oil-based muds provide an efficient method of limiting the extent of the fluid loss invaded zone however, it is impossible to eliminate fluid loss entirely since the formation of low permeability filter cake necessarily involve invasion.

Inclined Well and "Boycott Settling" Effect

Borehole deviation effects filtrate invasion due to formation of cutting bed on the lower side of the hole. The cuttings can settle much faster in inclined wellbores than in the vertical ones. Attributed to 'Boycott' settlings, the increase in settling rates is more evident if the wellbore is incline to 40^o- 50^o.

Discovery of this phenomenon is attributed to the physician A.E Boycott, who reported in 1920 that blood capsules settled faster if the test tubes were inclined. Similar behavior has been observed in drilling mud. In some fluids tested under static conditions, a thin layer of clarified fluid appear immediately below the upper wall of the hole, while cuttings settle vertically and form a cutting bed on the lower wall. Coincident with a downward slide of the bed, a resulting cross-section density gradient generates a pressure imbalance. This causes convection currents which drive the lighter fluid up and the bed down, accelerating settling. In many cases, mud circulation enhances the Boycott effect. As a result, cutting can settle much faster under dynamic conditions. Increases in mud velocity, viscosity, and gel strength help reduce, but do not eliminate, dynamically enhanced Boycott settling.

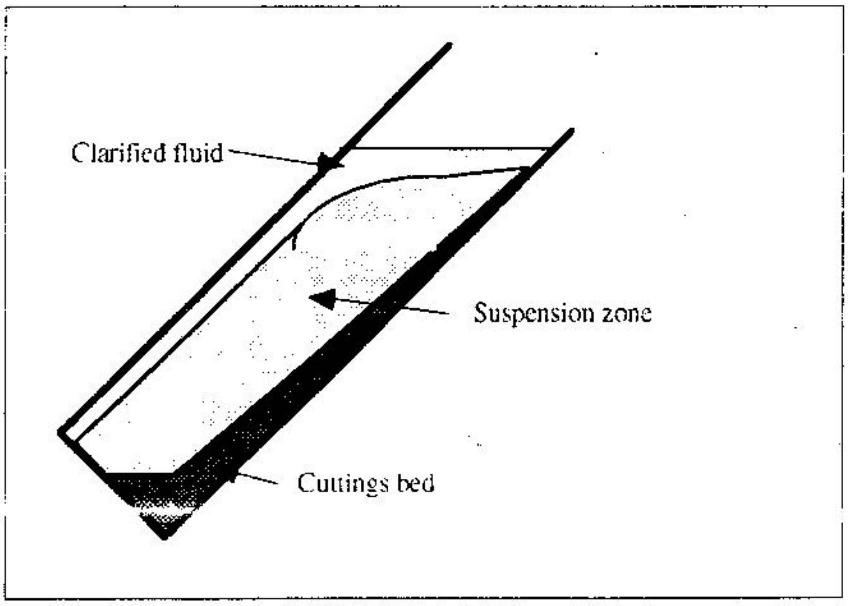


Fig.1.1 "Boycott" settling in an inclined conduit.

UNDERLYING PROBLEMS

One function of drilling fluids in rotary drilling is the lifting of cuttings up the annulus. Adequate cuttings removal from a well during rotary drilling is critical for cost-effective drilling. Increasing hole inclination from vertical aggravates the tendency for annular cuttings accumulation. Cuttings transport in vertical wells has been studied by many investigators. The problem of cuttings transport is significantly different in deviated wells than in vertical wells. Recently, increasing attention regarding cuttings transport has been given to directional drilling. Tomren, Iyoho[8], Backer[10], and Okrajni[11], among others, have conducted studies in this area.

Sample and Bourgoyne[12], showed that the most relevant parameter is the settling velocity of the cuttings in the stagnent mud and proposed a device to measure the settling velocity at the wellsite. Gavignet and Wick[13], recently showed that the existence of yield stress in the rheogram of the drilling fluid strongly influences the settling velocity and proposed a general method for calculating settling velocities from the polynomial fitting of multispeed rheometer, thus eliminating some of the uncertainties in the previous methods for designing cuttings transport in drilling.

Many factors affect cuttings transport. Previous investigators have listed the most relevant factors are (1) fluid annular velocity; (2) hole inclination; (3) drilling fluid properties; (4) penetration rate; (5) pipe/hole eccentricity; (6) hole geometry; (7) annular velocity; (8) particle density, settling velocity, size, and geometry; (9) drillpipe rotary speed; and (10) pipe/hole diameter ratio.

Tomren et al., observed that (1) when deviation from vertical is $< 10^{o}$, cuttings transport is essentially similar to the vertical situation; (2) when deviation increases, a cuttings bed develops at low flow rates; (3) for a given flow rate, the bed thickness increases with deviation up to an angle where it becomes independent of deviation angle; and (4) in given conditions of deviation and flow rate, the bed thickness is strongly influenced drillpipe eccentricity, but only moderately influenced by fluid viscosity.

Recent papers have expressed different viewpoints on the role of formation damage in the performance of horizontal wells. Some[3,4] suggest that, as horizontal well length increases, the influence of formation damage on total pressure drop can be negligible, resulting in additional advantage over vertical wells. Others[5] indicate that the damage zone may effect productivity more in horizontal wells than vertical wells and skin damage sometimes can prevent horizontal wells projects from succeeding. These two opposing interpretations of the influence of formation damage on horizontal-well productivity come from a lack of well-defined criteria (reservoir and well characteristics) to quantify the effect of formation damage on the flow efficiency of horizontal wells.

A model comparison between the flow efficiencies of vertical and horizontal wells Renard,G. and Dpuy,J.M[6] indicated that the permeability reduction around wellbore is less detrimental to horizontal wells and the effect of damage around a horizontal wellbore is reduced slightly by increasing the well length. Conversely, if the vertical permeability k_H is less than the horizontal permeability, k_V ,the anisotropy ratio, $\sqrt{k_H/k_V}$, magnifies the influence of formation damage near the horizontal wellbore. Gilman[7], also showed the greater flow -rate loss that damage inflicts on horizontal wells compared with vertical wells.

Theoretically, these reseachers considered the radial shape around vertical well is identical to horizontal well. As such they have included a skin value derived for an isotropic formation in a flow equation that otherwise accounts for anisotropy. Some practical consideration, however, is not adressed in Renard and Dupuy's paper. Fig 1.2 and fig 1.3 show two conceptual models for vertical-well damage and horizontal-well damage respectively. When the vertical permeability anisotropy (I_{ani}) is significant, the damage shape is not radial.

Therefore beside attempting to minimize fluid loss in preventing damage during drilling an inclined and horizontal wells, it must be accompanied by obtaining information on the nature of the damage which is must be correctly characterized to quantify its effect on production adequately. Additionally , to design an appropriate damage-removal treatment in the future becomes effective.

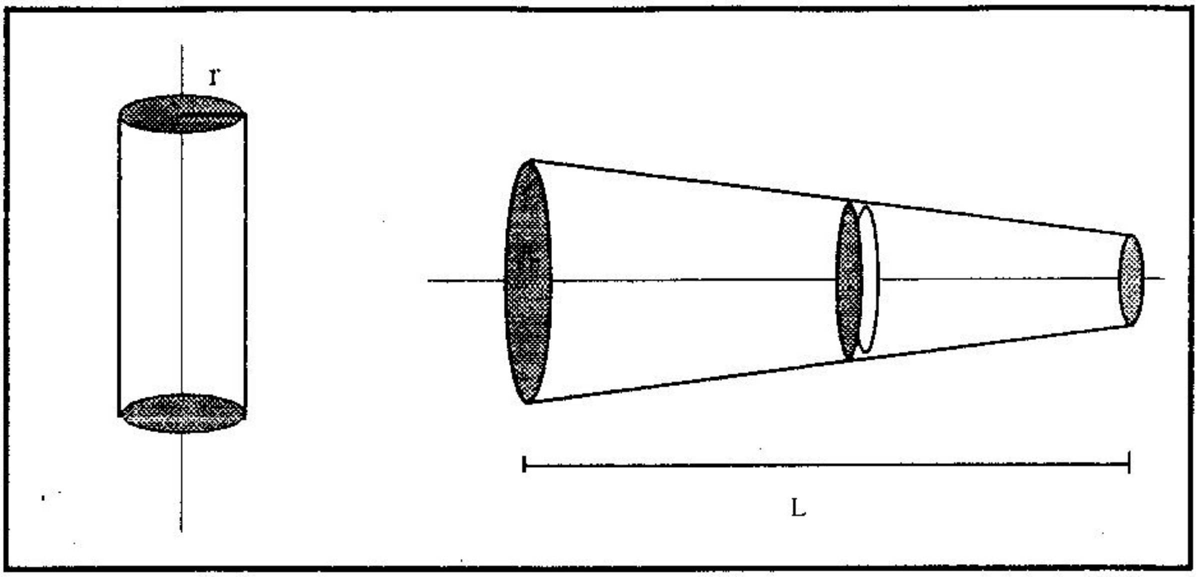


Fig 1.2 Damage shape along vertical and horizontal wells (After Economides,1991)

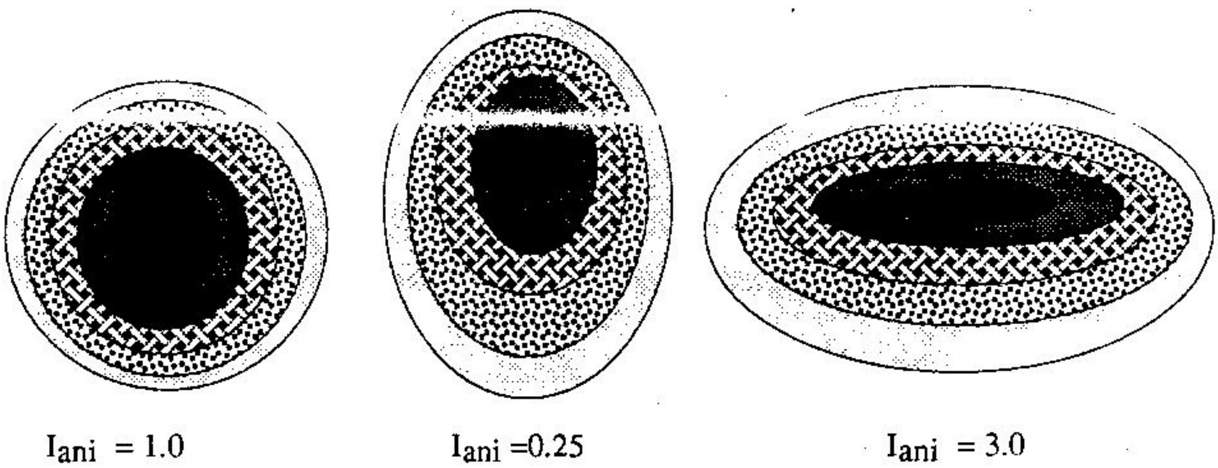


Fig 1.3 Cross section of the permeability distribution around horizontal wells for different permeability anisotropies (After Economides,1991)

OBJECTIVES

The objective of this research is to provide basis for comparing the shape and degree of damage resulting from drilling inclined well to vertical wells.

There are **three** main objectives that can be summarized as follows:-

- ❑ To identify the shape and distribution of damage surrounding the inclined and horizontal wells.
- ❑ To evaluate systematically the damage severity surrounding the inclined and horizontal wells.
- ❑ To develop a new technique in engineering core flow test of formation damage laboratory evaluation on the basis of return permeability using long multitap permeameters.

The research area is of specific interest for EOR and drilling deviated and horizontal well project. In EOR, if the conductivity of injection and producing wells is damaged, sweep efficiencies and recovery factors will be adversely effected. The success or failure of an EOR project may depend on the ability to inject planned amounts of specific fluids and to produce oil at adequate rates.

The method in this research which is flexible and practically oriented, allows formation-damage evaluation under following conditions;

- ❑ dynamic and static filtration, < 100 psi differential pressure, 6-ft/sec [2-m/s] annular velocity, 2-in. core diameter, 12 in.core length, simulated drilled cutting of various sizes and 16 bits resolution with 16 channels data acquisition system.

In this experiment 1 foot long homogeneous cores were used. Permeameters were made by moulding these cores with resin. Pressure drop measurement of these permeameters before and after exposing to the dynamic and ststic filtration can give an indication of any permeability changes in term of return permeability. Return permeability, Kf/Ki is defined as a ratio of effective permeability after mud circulation upstream of a core at overbalance pressure, to the pre-exposure effective permeability in the production direction. Details of the distribution of permeability changes were analyzed and from this results the shape of damage for inclined well was illustrated.

Two aspects of the work were reported in this experiment. First, return permeability measurements were indicated by the reduction of permeability values (percentage)which were those computed from pressure drop data for single phase flow tests. Secondly, the permeability ratio (K_f/K_i) distribution around the inclined wellbore. Only water mud system was selected for this experiment, and the mud rheology (density, viscosity, pH, fluid loss, solid content) and the system (flow rate, operating pressure) were kept consistently throughout of the tests.

From these two sets of experiments a number of aspects of formation damage by drilling fluid can be identified which were including the degree and shape of damage, while the mechanism of damage were not investigated. Analytical expressions of the permeability is derived assuming steady- state flow on an incompressible fluid in homogeneous anisotropic medium.

EXPERIMENTAL APPROACH

Engineering Core Flow Tests

Frequently, flow tests are run in laboratories on reservoir core material under downhole conditions involve only overall permeability across short cores, 1 to 3 in. long. Observation and results from these short-core studies have often been extrapolated to predict core permeability response beyond 3 in. The effects of secondary reactions, precipitation, fine migration and adsorption may not be observable from short-core studies.

In the earlier study, a method that allows evaluation of formation damage was established by Keelan and Koepf[15] and recently, improved by Marx et al[16].

Short core holder was constructed according to principle of Hasler cell. Core was mounted in rubber sleeve and an overburden pressure of 2,000 psi was applied. The evaluation is based on two factors; damage ratio(DR) and sectional damage ratio (SDR). The residual permeability is expressed in terms of relative values, with the initial permeability as reference. The depth of the permeability impairment is determined by measurement of the length of segmented cores. For this criterion the SDR term was introduced.

$$DR = 100\ K_f / K_i$$

A similar technique presented by Krueger et al.[17]. In this method core samples are segmented and loaded in the holder, and the permeability of individual segmented sections are determined after exposure of one end of the core assembly to drilling fluid. This Approach involves sample loading and unloading to remove different segments starting from the mud exposed end of the core assembly. If this test is performed at reservoir conditions, the data would be influenced by stress cycling and stress hysteresis.

Each of the previous studies has limitations. To overcome these limitations, the study on evaluation of formation damage had to be a step advanced to explore a new technique on core analysis. A long permeameter able to measure real-time permeability changes at several locations along a single piece of core up to 3 ft in length is designed and fabricated.

In general the whole tests in this study can be devided into the following order:

Steps	Facilities
❑ Saturating permeameter - with brine	saturation apparatus
❑ Measuring initial permeability - Ki, with brine (production direction)	return permeability test facility
❑ Damaging permeameter - with water based mud, 2 hrs. dynamic, 1 hr. static, 1 hr. ststic (injection direction)	dynamic column test rig

- Measuring return permeability. return permeability test facility
  - Kf, with brine (production direction)

To meet the above requirements, several tests apparatus were designed and fabricated. They are:

- Permeameters
- Return Permeability Apparatus
- Dynamic column test rig

MAKING PERMEAMETERS : A NOVEL STATE OF THE ART

A schematic diagram of making a permeameter from a long sandstone core is shown on fig. 1.5.

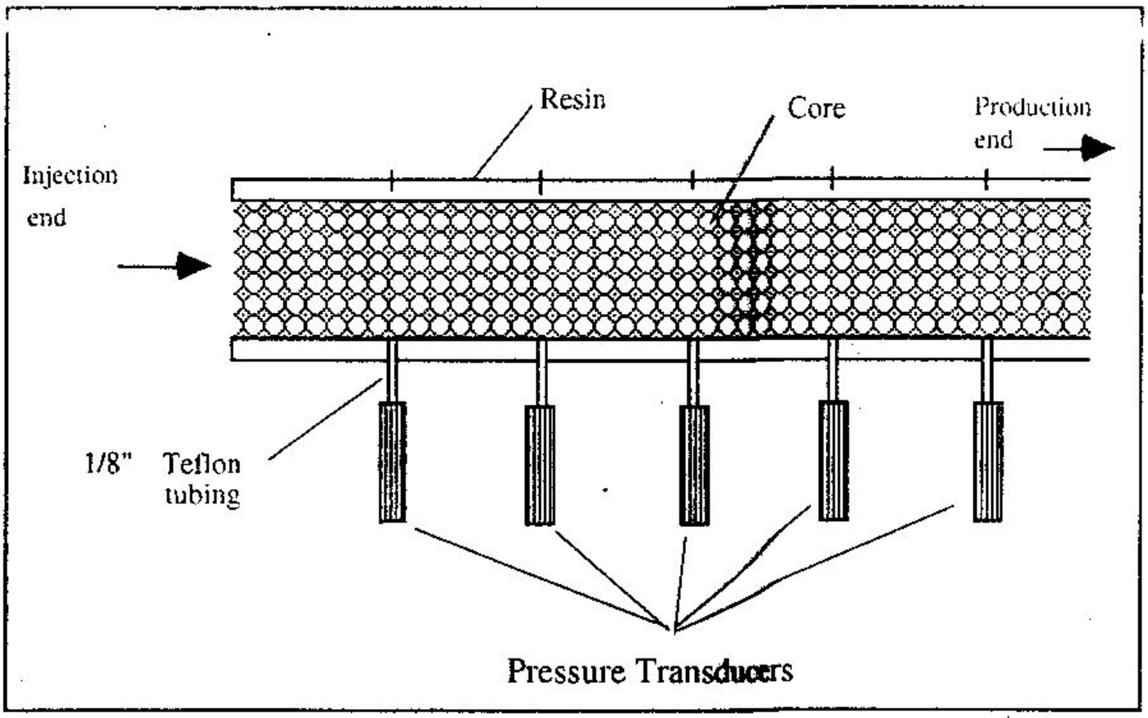


Fig. 1.4 Cross-Section of Multi-Pressure Tapped Long Core Permeameter

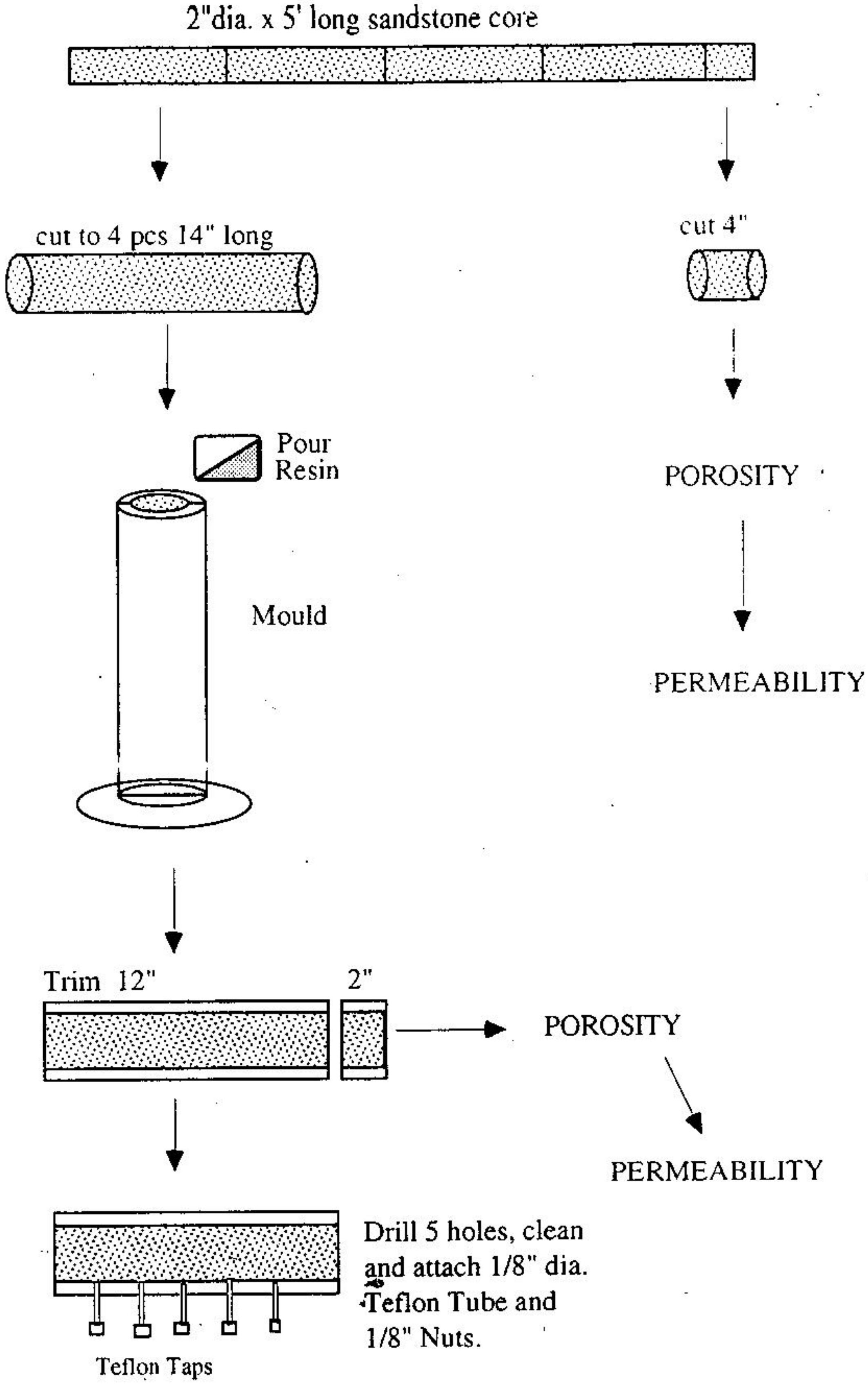


Fig 1.5 Schematic diagram of making a permeameter from a long sandstone core

Sample Positioning On Dynamic Filtration Column

There were two permeameter holders available at the Dynamic Filtration Column. Both are opposite to each other and located at 3.5 meters from the mud inlet. Two permeameters can be exposed to damage on the column at a time. Pressure drop profile during filtration on both permeameter can be recorded through 12 channels available in data acquisition card. The permeameters are exposed to damage at five orientations for each horizontal and inclined positions.

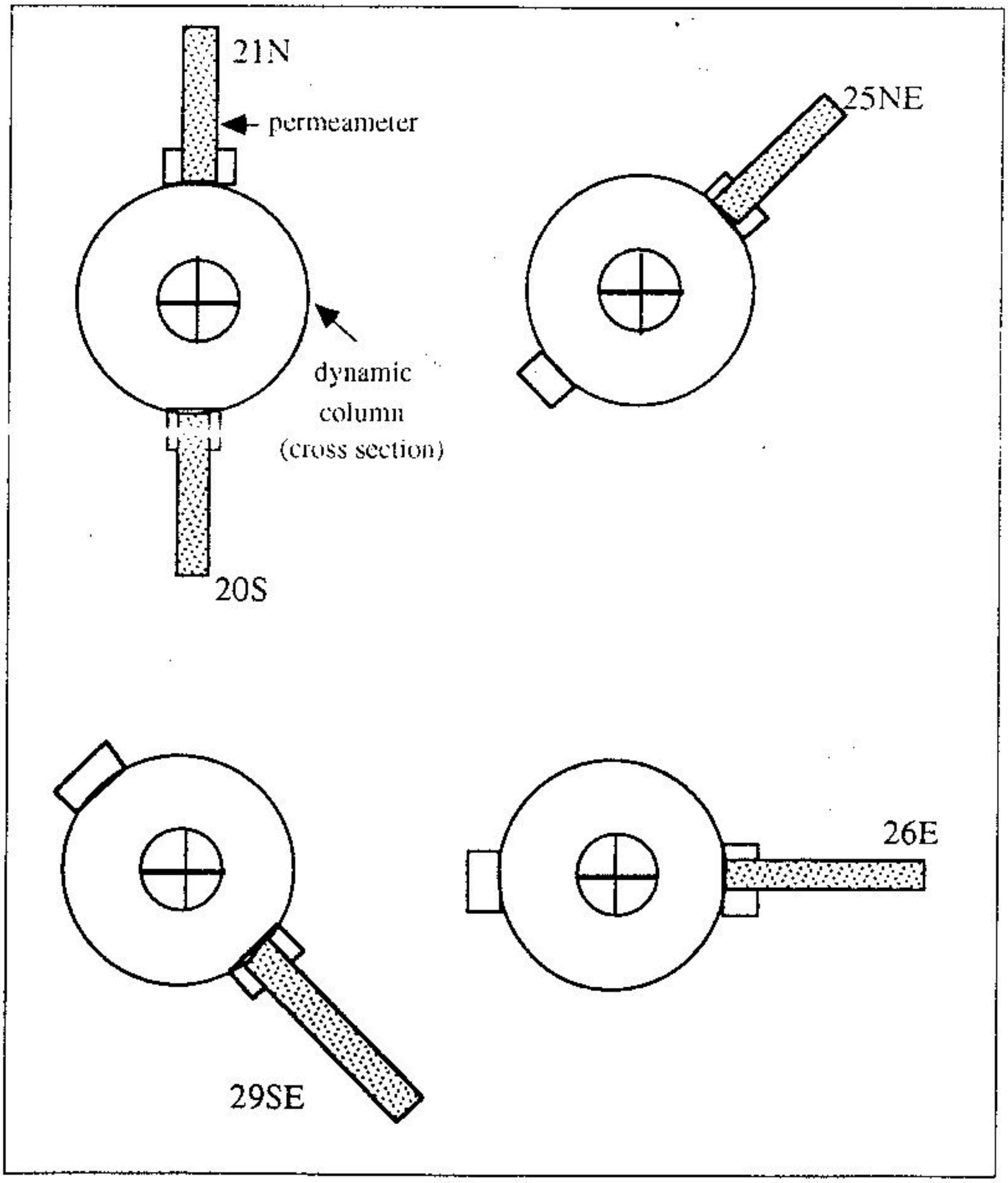


Fig 5. An illustration shows 5 permeameters position at different orientations located on the Dynamic Filtration Column.

RETURN PERMEABILITY APPARATUS

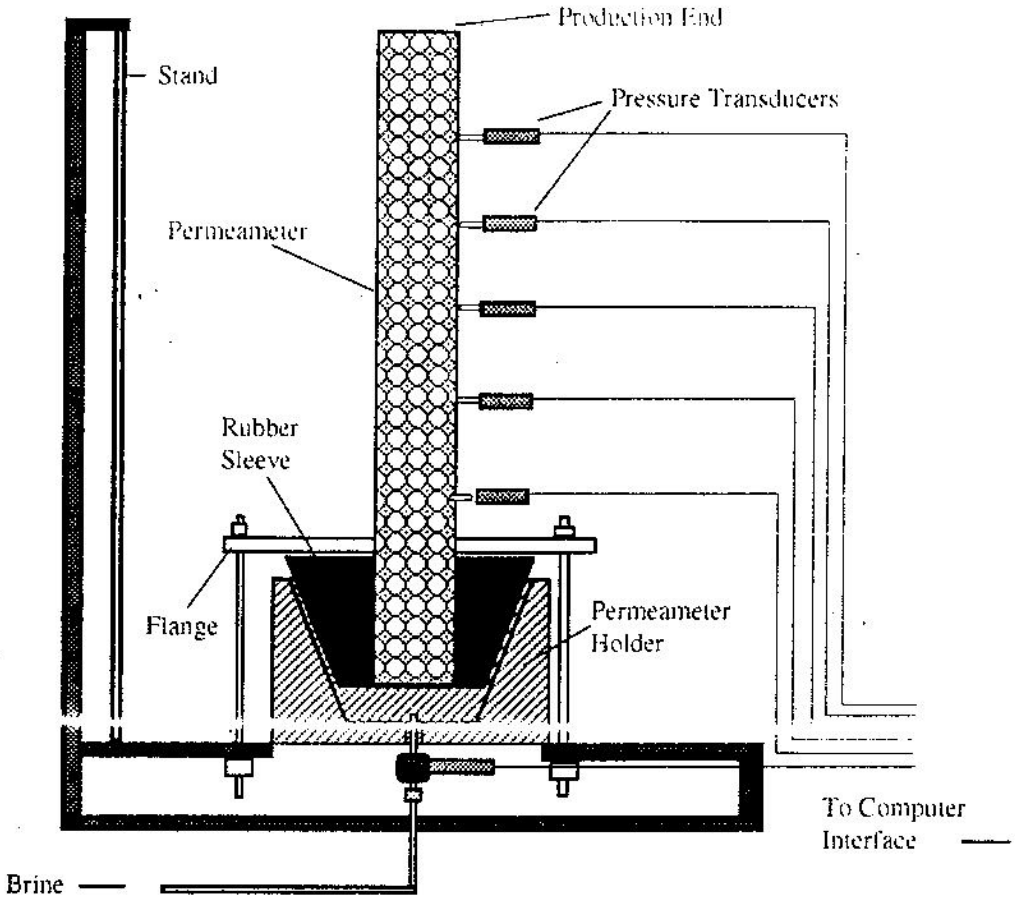


Fig 1.6 Return Permeability Apparatus

DYNAMIC COLUMN TEST RIG

The dynamic filtration column consists of stainless steel outer pipe and inner shaft . The outer pipe has an inside diameter of 102 mm and the inner shaft has an outside diameter of 60mm. The entire column length is about 3 meters. Drilling fluid enters the column at the bottom inlet and flows up through annular space across the face of two core samples in coreholders which is mounted in the wall of outer pipe. Fig. 1.7 is a schematic of the complete facility.

The test apparatus was designed and constructed in accordance with the following requirements:-

- annular-laminar-flow of steady -state condition must prevail in every test case,
- allows a selection of drilling flow-rate and
- allows a selection of well inclination from vertical to horizontal.

The test apparatus consists of following major components:-

1) Circulating system: to transport drilling fluid and injected solids,

2) Drill solid injection port.

3) A section of annulus long enough to create annular-laminar of steady-state flow,

4) A 140rpm rotating inner shaft : to represent a dynamic drilling of an average field condition,

5) Direct -Mass Flow Meter: to record flow-rate during circulation

6) Hydraulic superlift: a mean of varying the angle of inclination of the tests section.

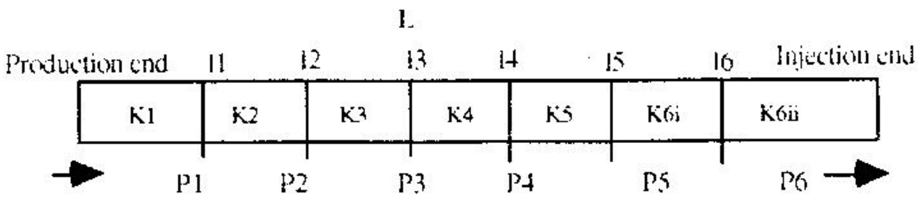
7) A jet type spray nozzle for efficient mud mixing

8) Two sets of core holders: located at 3.5 meters from mud inlet.

RESULTS

Fig 1.8 and 1.9 present return permeability result for 2 permeameters located at upper side of the inclned column (permeameter 21N) and at lower side of the inclined column (permeameter 20S). Examination of permeability changes vs cumulative flow (PV) curves for permeameter 20S shows that the permeability changes occur most severely at K_{6ii}, decrease at K_{6i} followed by K_5, K_4, and almost unchanged or slightly change at K_3, K_2, K_1 locations. The permeability changes for permeameter 21N, however, shows that permeability change occurs almost at all location from K_{6ii} to K_1 . This pattern is also shown by other samples (25NE, 26E and 29SE).

Table 1.1 shows the value of permeability changes for all permeameters and productivity loss is calculated as follow:



$$q = \frac{K_o A \Delta P_T}{\mu_o L}$$

$$\Delta P_T = \Delta P_1 + \Delta P_2 + \Delta P_3 + \ldots\ldots + \Delta P_7$$

$$\frac{q_o \mu_o L}{\bar{K} A} = \frac{q_o \mu_o l_1}{K_1 A} + \frac{q_o \mu_o l_2}{K_2 A} + \frac{q_o \mu_o l_3}{K_3 A} + \ldots\ldots\ldots\ldots + \frac{q_o \mu_o l_7}{K_7 A}$$

$$\frac{L}{\bar{K}} = \frac{l_1}{K_1} + \frac{l_2}{K_2} + \frac{l_3}{K_3} \ldots\ldots\ldots\ldots + \frac{l_7}{K_7}$$

$$\bar{K} = \frac{1}{\left(\frac{l_1}{L}\cdot\frac{1}{K_1} + \frac{l_2}{L}\cdot\frac{1}{K_2} + \frac{l_3}{L}\cdot\frac{1}{K_3} \ldots\ldots\ldots\ldots + \frac{l_7}{L}\cdot\frac{1}{K_7}\right)}$$

From table 1.1, a trend of decreasing in productivity loss can be seen from permeameter 21N (the upper side of the test column wall) as we go to the side and down to 25NE (the lower side of the test column wall). A more clear damage trend can be seen on fig 1.10, when permeability ratio Kf/Ki is plotted against permeameter length. It shows that at the upper side of the test column wall(21N), mud damage occur severily with grerater depth, while as we go to the sideand until the bottom of the wall, it shows that the damage is less severe and occur at shallow depth.

FIG 1.8 PERMEABILITY CHANGE IN PERMEAMETER 21N AFTER BEING EXPOSED TO MUD DAMAGE

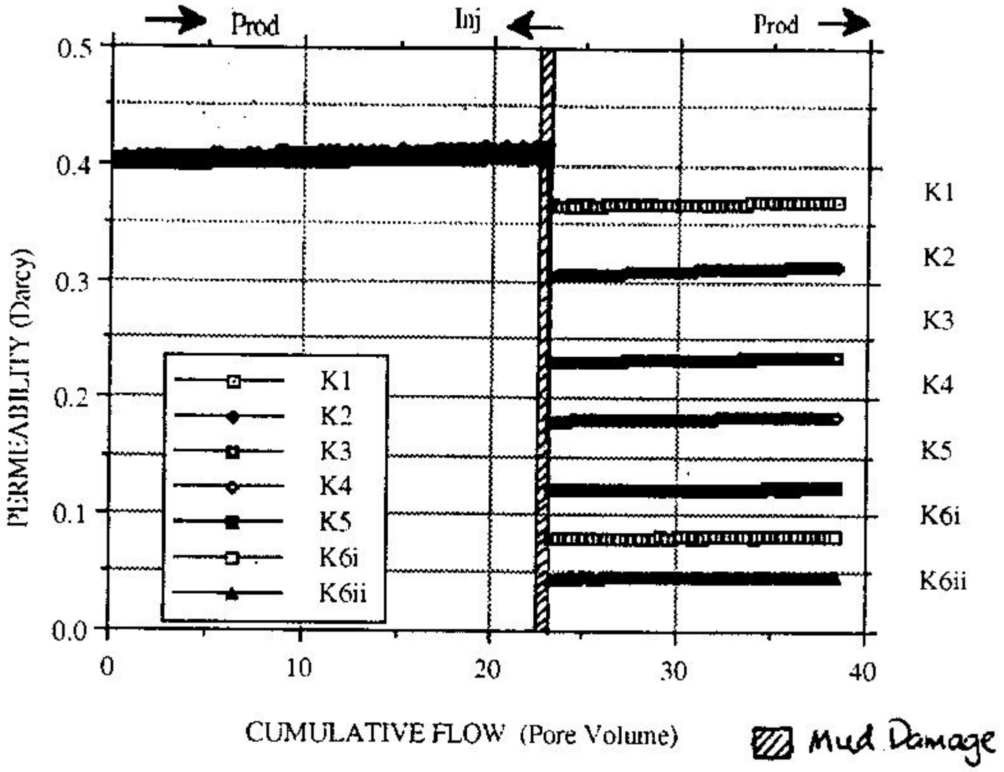


FIG 1.9 PERMEABILITY CHANGE IN PERMEAMETER 20S

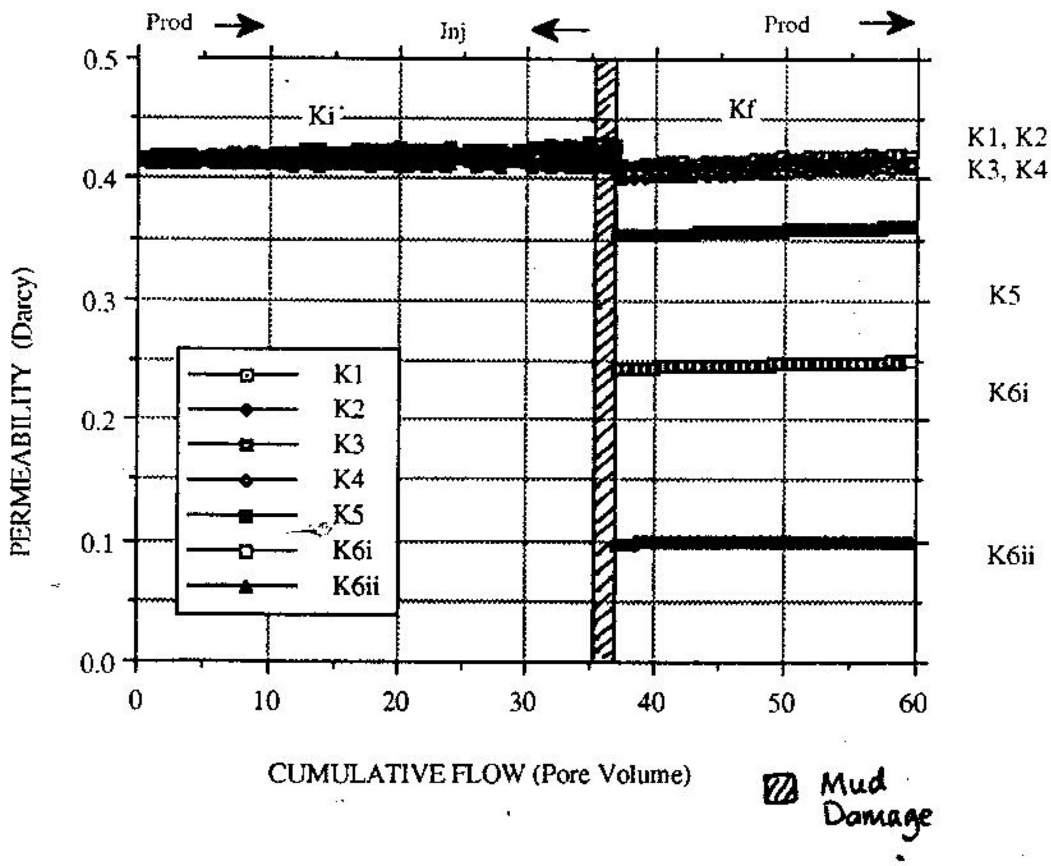


TABLE 1.1 PRODUCTIVITY LOSS AROUND INCLINED WELLBORE

SAMPLE NUM.	L, cm	Ki, mD	Kf, mD	DR = Kf/Ki mD	Average Ki,mD	$\bar{K}$, mD	Productivity Loss .=(1-K/Ki)x100
	0.0	0	0.0000	0.0000			
	2.0	0.4033	0.0458	0.1136			
	6.0	0.4033	0.0803	0.1991			
	11.0	0.4089	0.1213	0.2966	0.4064	0.1480	63.58%
21N	16.0	0.4101	0.1821	0.4440			
	21.0	0.4055	0.2326	0.5737			
	26.0	0.4093	0.3101	0.7577			
	32.0	0.4046	0.3679	0.9091			
	0.0	0.0000	0.0000	0.0000			
	2.0	0.4165	0.0334	0.0801			
	6.0	0.4165	0.1024	0.2458			
25NE	11.0	0.4187	0.2048	0.4892	0.4173	0.1743	58.23%
	16.0	0.4183	0.2768	0.6619			
	21.0	0.4201	0.3202	0.7624			
	26.0	0.4158	0.4105	0.9873			
	32.0	0.4152	0.4160	1.0020			
	0.0	0.0000	0.0000	0.0000			
	2.0	0.4009	0.0403	0.1006			
	6.0	0.4009	0.0809	0.2017	0.4033	0.1597	60.40%
26E	11.0	0.4014	0.1618	0.4032			
	16.0	0.4024	0.2306	0.5730			
	21.0	0.4029	0.2874	0.7133			
	26.0	0.4045	0.3191	0.7888			
	32.0	0.4102	0.3822	0.9318			
	0.0	0.0000	0.0000	0.0000			
	2.0	0.3875	0.0786	0.2028			
	6.0	0.3875	0.1614	0.4165			
29SE	11.0	0.3933	0.2397	0.6095	0.3907	0.2475	36.67%
	16.0	0.3932	0.3202	0.8142			
	21.0	0.3892	0.3636	0.9341			
	26.0	0.3893	0.3703	0.9514			
	32.0	0.3950	0.3914	0.9910			
	0.0	0.0000	0.0000	0.0000			
	2.0	0.4129	0.0987	0.2390			
	6.0	0.4129	0.2464	0.5968			
20S	11.0	0.4213	0.3564	0.8461			
	16.0	0.4199	0.4066	0.9684	0.4174	0.3148	24.58%
	21.0	0.4185	0.4086	0.9762			
	26.0	0.4178	0.4120	0.9863			
	32.0	0.4186	0.4153	0.9919			

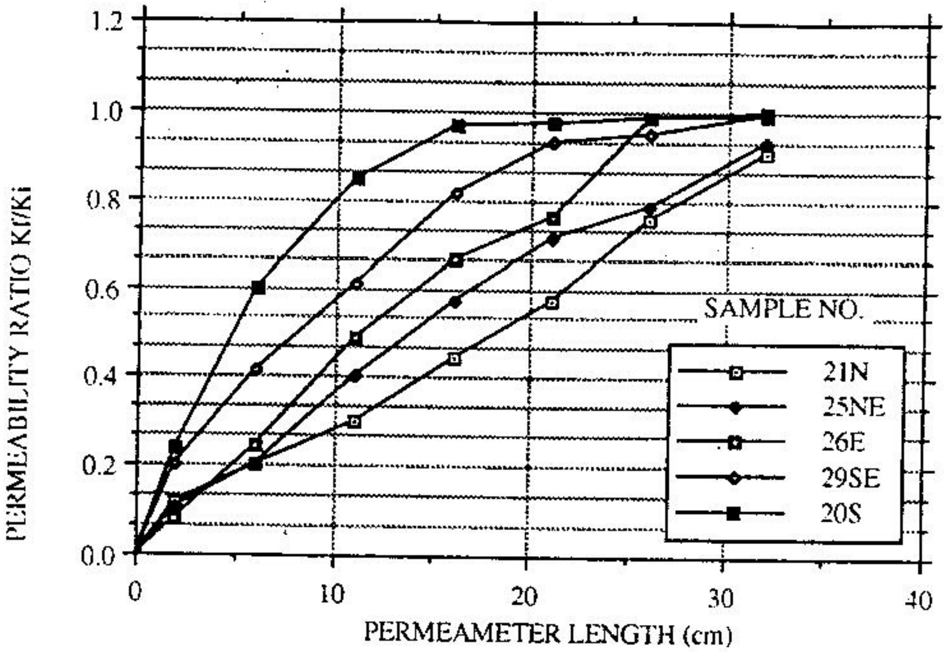


Fig 1.10 PERMEABILITY RATIO AS A FUNCTION OF PERMEAMETER LENGTH FOR INCLINED WELLBORE

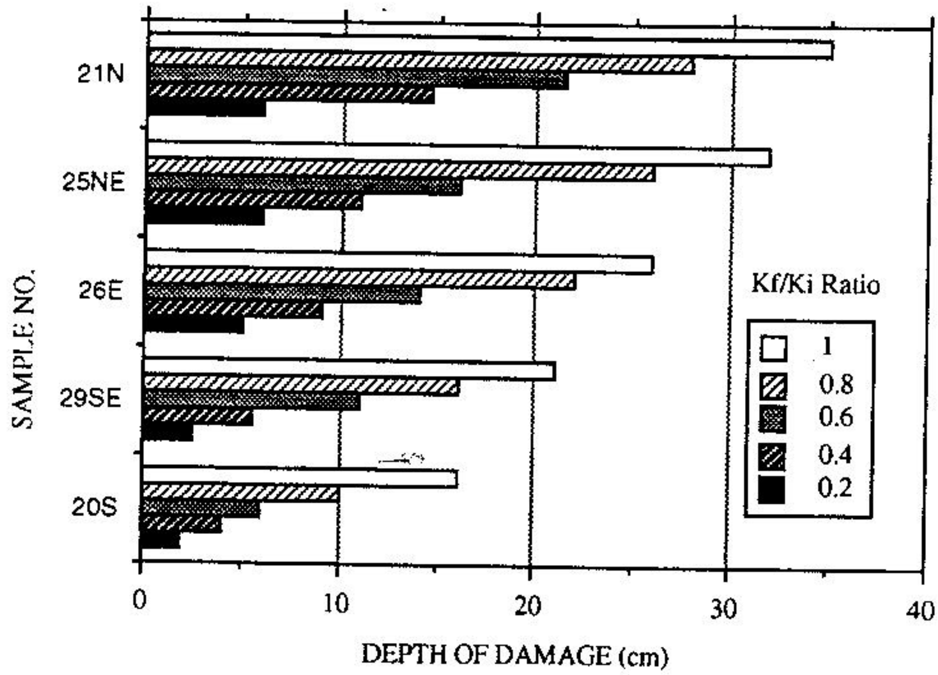


Fig. 1.11 SEVERITY OF DAMAGE AROUND INCLINED WELLBORE

Fig 1.11 shows the depth of damage obtained from the permeability ratio distribution along the permebility ratio curve (Fig 1.10). Based on the fig 1.11, the shape of damage around inclined well then illustrated as follow:

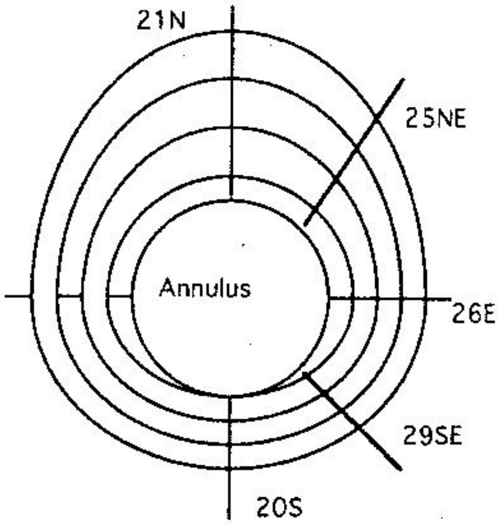


Fig 1.12 An illustration of damage shape around inclined annulus..

On the basis of the permeability ratio distribution around inclined annulus above, the following conclusions can be drawn regarding the shape and severity of mud damage in inclined annulus:

1. The shape of damage in inclined wellbore is not radial. It is an elliptical shape.
2. The customary use of conceptual model of radial damage shape as reference in evaluating/ predicting flow efficiency of an inclined well should be restricted to vertical well. For inclined well, the damage shape is elliptical.
3. The depth of mud damage at the upper side of the inclined annulus wall is greater than the depth of damage at the lower side. This difference can be used to confirm an explaination of formation of cuttings bed at the lower wall of inclined annuli observed by previous reaserchers.

DISCUSSIONS

Based on the result, the damage occur most severe at the upper side of the test column wall could be due to more fluid or solid intrusion occur at the upper side than the lower side of the test column wall. Permeability changes could be possibly caused by fresh water invasion which assumed to be associated with swelling clays, or/and fines migration and bridging pore throats. Since the filtration's flow rate is independent of gravitational field, the distance of fluid intrusion into the upper and lower side of the boreholes should be the same. If one considers the force causing filtration to occur then, in the lower side of an inclined annulus, gravity and the Boycott effect would assist the differential pressure in forming a filter cake. On the upper side gravity would oppose particulate deposition during static exposure and erosion continuously occur during dynamic exposure. The effect of gravity here is to create a particulate concentration gradient across the borehole which result in settling of heavier solids particles such as sand and barite. As a result, at the upper side of the annulus have more fluid/solid invasion and at the lower side of the annulus have less fluid/solid invasion. Although an internal filter cake could be formed to stop fluid invasion, but since at the permeameters' face of the upper side erosion might occur continuously, the formation of internal filter cake will take some times. These combined effects will substantially influence the shape and the degree of damage around an inclined annulus.

Investigations by Tomren and Iyoho, indicated that the formation of a cuttings bed in an annulus is the phenomenon that accompanies the cuttings transport in an inclined annulus. The cuttings bed is, of course, a result of transport; however, its presence affects continuous transport until steady-state conditions are reached. Because of the presence of a cuttings bed, the effects not observed in a vertical annulus are experienced in the inclined one-saltation flow, heterogeneous and pseudohomogenous flows. These effects are caused by a kind of interaction between flowing mud and the cuttings bed that is being formed.

Under certain conditions, the cuttings bed slides along the lower wall of the inclined annulus[8,10,11]. This was observed for 40^0 and 45^0 angles of inclination at relatively low annular mud velocities. This effect was dominant, nullifying the influence of other parameters and resulting in the worst transport (highest final annular particle concentration). This observation has an important practical significance to the effect of fluid invasion in inclined annulus.

Beyond the mud axial flow, a tangential flow will be experienced while the inner pipe is rotated. A minor effect of turbulence will be observed as a result of this tangential flow. Furthermore, because of the presence of the cuttings bed, a mechanical action of rotating pipe on the bed can be expected. These factors should influence the cuttings transport and fluid invasion in the inclined annulus. However, previous work (Iyoho,) found this to be negligible.

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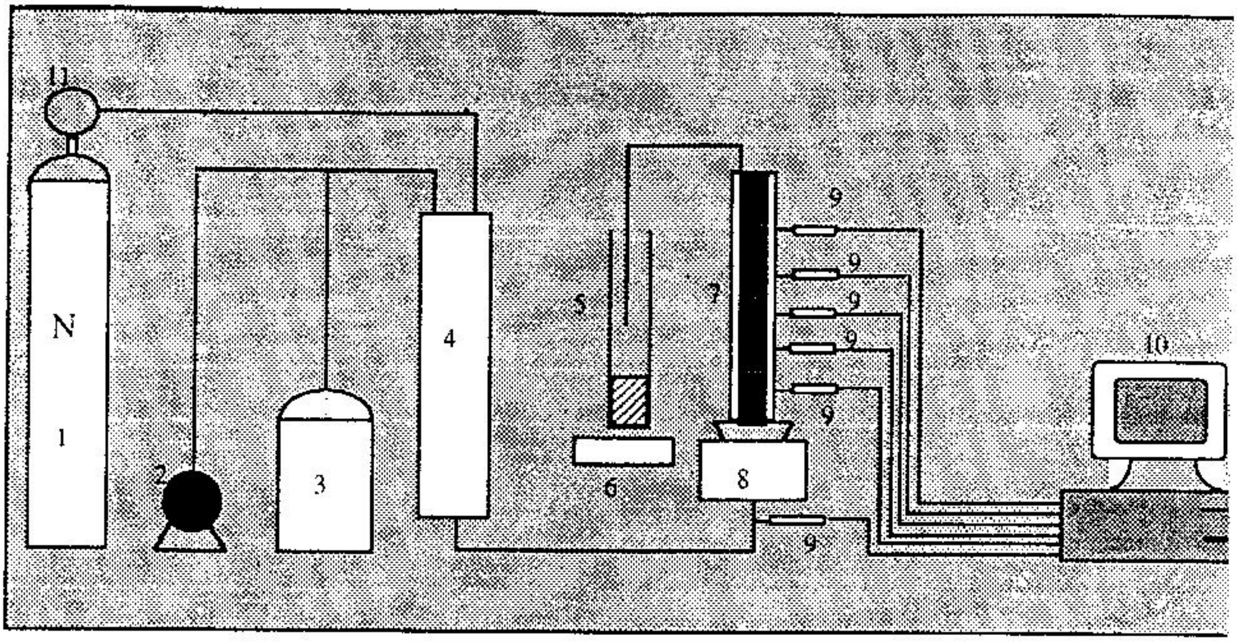
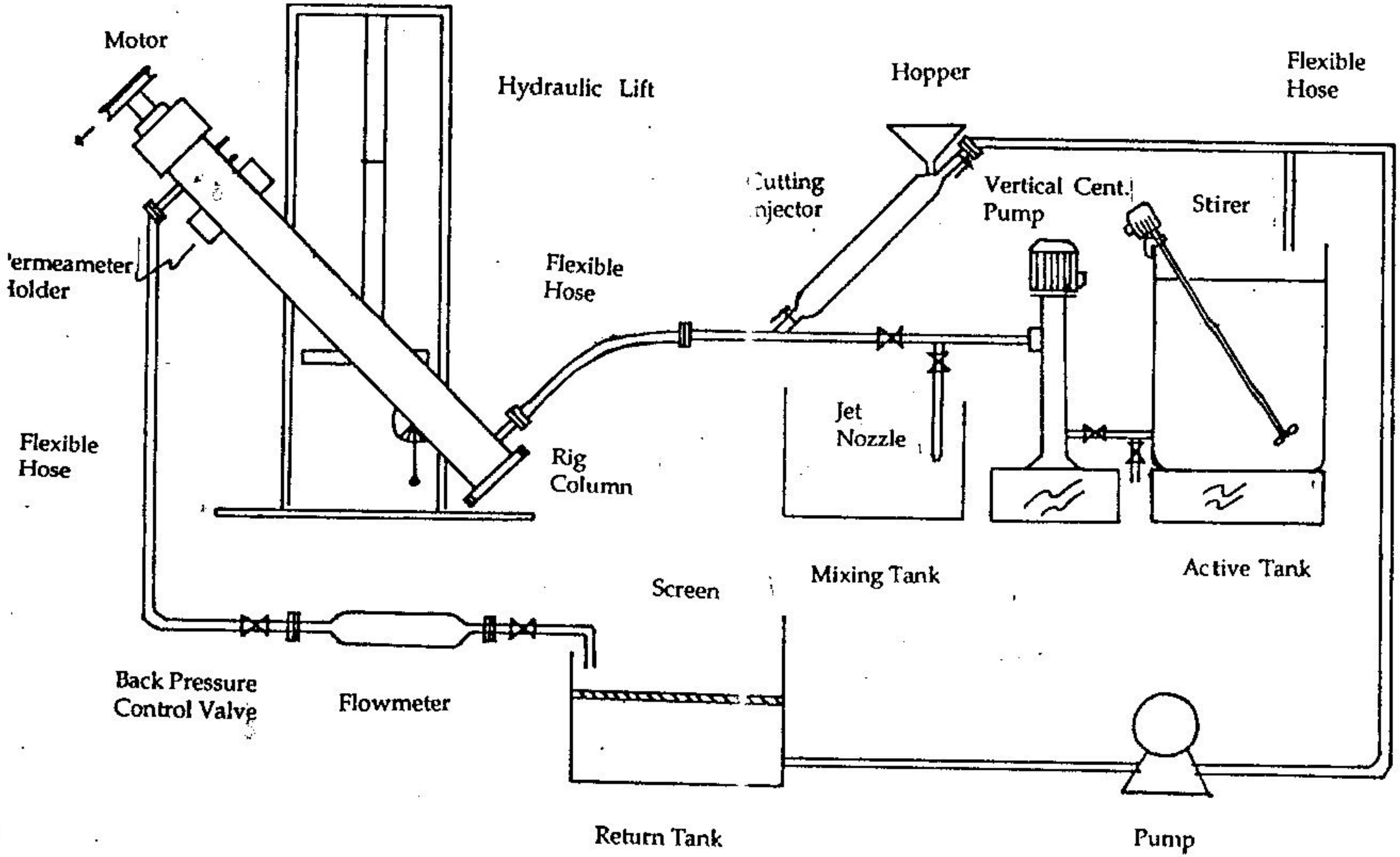
<u>APPANDIX A</u> RETURN PERMEABILITY SETUP



1 Nitrogen Tank
2 Vacuum Pump
3 Brine Tank
4 Accumulator
5 Measuring Cylinder
6 Balance
7 Core
8 Core Holder
9 Pressure Transducers
10 Interfacing Card & Computer
11 Regulator


Motor
Hydraulic Lift
Hopper
Flexible Hose
Cutting Injector
Vertical Cent. Pump
Stirer
Permeameter Holder
Flexible Hose
Flexible Hose
Rig Column
Jet Nozzle
Mixing Tank
Active Tank
Screen
Back Pressure Control Valve
Flowmeter
Return Tank
Pump

APPENDIX. B