NEW CORING SYSTEM REDUCES FILTRATE INVASION

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Abstract Core analysis can be seriously impaired by coring fluid filtrate invasion. This invading filtrate, which frequently contacts the entire core, detracts from the quality of laboratory measurements of *in situ* fluid saturations, rock wettability, and permeability. Since major reservoir decisions may depend on such information, it is important that the measurements are carried out on uninvaded core.

Filtrate invasion occurs in three principle areas during coring: (1) ahead of the bit, (2) in the bit throat, and (3) inside the core barrel. A new low invasion coring system has been developed which reduces fluid invasion in all three areas. Examination of the fluid dynamics in each of the respective areas shows how filtration can be minimized through specific designs of the core bit and the inner tube pilot shoe. The low invasion coring system combines application of this new equipment with proper coring parameters and a low spurt loss coring fluid.

The system was field tested very successfully in the Stevens sandstone in the Elk Hills field (California). Filtrate tracer and fluid saturation results show no significant filtrate invasion or fluid flushing beyond 0.5 inch into the 4-inch diameter core, and indicate the invasion depth is not related to formation rock permeability. The system is a valuable tool for providing quality core samples suitable for accurate laboratory analyses.

INTRODUCTION

One of the primary reasons for taking a core is to perform tests and analyses that aid in characterizing the properties of the reservoir formation. Major reservoir decisions are made from data gathered from these analyses, which may include *in situ* fluid saturation, rock wettability, and permeability.

A major factor affecting the validity of these measurements is the intrusion of the fluid phase of the coring mud into the core. *(Nowak, et.al., 1951;* Hassen, 1980; Ferguson, et.al.) This intrusion is commonly referred to in the literature as *filtrate invasion.*

Numerous methods have been used to quantify filtrate invasion, including the use of tracer materials added to the mud system. *(Hagedorn, et.al., 1972; Bilhartz, et.al., 1978; Core Laboratories, 1988)* Results of these techniques and others have shown that initial oil saturation is altered, and most likely decreased, by fluid invasion. *(Jenks, et.al., 1968)* A number of papers have described the phenomenon of filtrate invasion with respect to time (dynamic filtration or spurt loss) as a function of rock and coring fluid properties. *(Eckel, 1954; Horner, et.al., 1957; Young, et.al., 1967; Evans, et.al., 1972)*

Full scale laboratory coring tests, some with confirming field test data, also have shed some light on the mechanics of filtration and its effects on high permeability consolidated and unconsolidated reservoirs. *(Black, et.al., 1985; Tibbitts, et.al., 1985)*

Filtrate invasion occurs in drilling and coring as a result of the fluid phase of the mud being driven into the formation by the application of a differential pressure. The invasion rate depends on the reduction of formation permeability caused by shallow invasion of particles at the cut surface. As the bit crown advances into the formation, these particles are repeatedly deposited and then removed by the cutters during each revolution.

A *systems approach* of mud, core bit and core barrel design was used to address the mechanics of dynamic filtration in terms of coring rate and fluid intrusion into the formation. *(Krueger, et.al., 1954; Glenn, et.al., 1957; Slusser, et.al., 1957)*

Coring parameters were tailored for use of this system in obtaining cores from the Stevens sands in the Elk Hills field near Bakersfield, California.

This paper describes both the mechanisms of filtrate invasion into the core, and the system designed to minimize filtration.

HARDWARE DESIGN

System Design

To design a low invasion coring system, it is helpful to understand where invasion takes place and the mechanisms involved.

Filtration invasion occurs in three principle areas during the coring process. One area is in the formation rock close to the bit crown, both ahead of and lateral to the bit. Another is in the throat of the bit where the core is cut, and the last is in the core barrel itself.

There are three additional factors that affect filtrate invasion in each of these major areas: One is the total time the core is subjected to coring fluid. A second is the degree to which the formation can be made impermeable to the filtrate at the surface of the core. Finally, the volume of coring fluid passing through the system per unit time is also an influencing factor.

The low invasion system must be designed (1) with proper geometry to minimize fluid filtration at the three principle areas described above; (2) to maximize the rate of penetration to reduce exposure time to the coring fluid; and (3) to allow pumping of the minimum volume of coring fluid necessary to balance both formation of an impermeable filtercake, and proper cleaning of the core head.

Filtration

Permeable formation rocks will conduct fluids if a differential pressure is applied. (Figure 1) A combination of solids, polymers, viscosifiers and other agents commonly are used to form filtercakes on and in wellbore surfaces to restrict filtrate invasion. *(Dresser Magcobar; Moore, 1986)* Filtercakes formed on the surface are called *external* filtercakes, where those formed internal to the rock are called *internal* filtercakes. Particles and polymers contained in the coring fluid are driven into the pores of a formation to bridge and plug the paths at restrictions called *pore throats.*

By designing a coring mud that quickly plugs up the pore throats of the formation, an effective quasi-static barrier to filtration is obtained and filtration to the core can be drastically reduced.

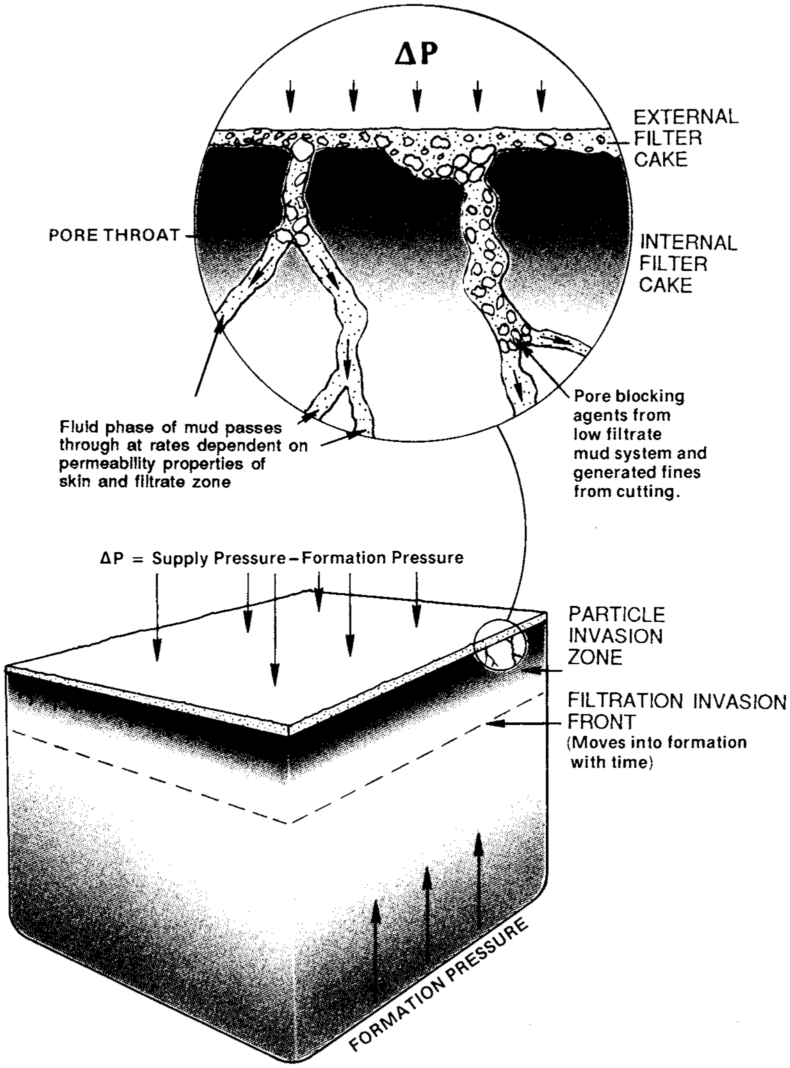


FIGURE 1. Illustration of dynamic filtration.

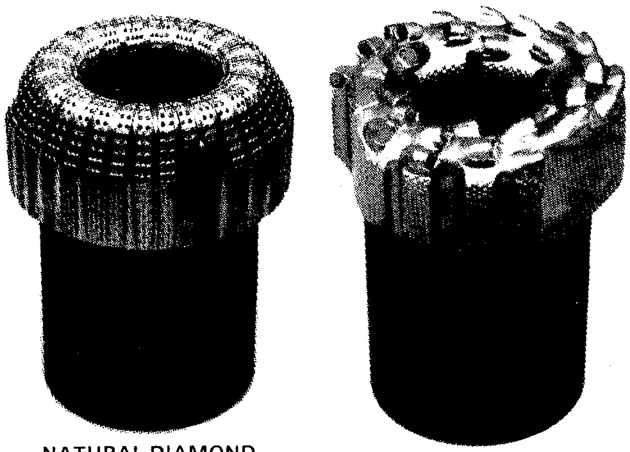
It is recognized that a particle size distribution which includes particles a fraction smaller than the diameter of the pore throats can be effective in controlling fluid loss into the core, in addition to controlling the depth and the degree of pressure gradients in the filtration zones ahead of and lateral to the core bit. *(Gatlin, et.al., 1961; Gatlin, 1960; Davidson 1979; Gray, et.al., 1980; Peltier, et.al., 1989)*

Once this plugging zone and its associated filter layer (cake) is formed on the core and in the formation ahead of the bit, it is *essential* to protect it from being disturbed. This is the key to preventing filtrate from entering into the core, and to obtaining high coring rates.

Conventional Coring

In lab experiments, core bits that show the highest filtration in permeable sands are those which resemble natural diamond core heads. This is not surprising considering what is happening at the cutter/formation interface: As the core head rotates into the formation, several hundred individual cutters cut into the external and internal filtercakes, exposing formation that is susceptible to rapid fluid intrusion (spurt loss). Since the formation is being cut at all of these locations simultaneously, the result is an almost continuous and complete flooding of both the formation and core with filtrate.

Most fluids currently used for coring have not been designed with low filtration properties in mind. As a result, when they are used, filtrate continues to permeate the core after it has entered the inner tube of the core barrel.


NATURAL DIAMOND CORE BIT

PDC CORE BIT

FIGURE 2. Conventional natural diamond and PDC core bits.

Natural diamond core heads (Figure 2) have hundreds of cutters in contact with the formation. The depth of cut per cutter is very small. The internal filtercake, which has the highest pressure gradient in the rock, is continuously cut.

It is believed that these high gradients effectively strengthen the formation, which lowers the rate of penetration. So, in addition to allowing continuous filtration, the low coring rate provides greater exposure time to drive filtrate deep into the zone ahead of the bit and throughout the core.

With conventional core heads, the outer diameter (OD) of the core is repeatedly scoured by natural diamonds that form the inner diameter (ID) gage of the core head. Because of the high driving fluid pressure at this location and the repeated scouring of the filtercake, the core is receiving filtrate almost continuously throughout the period of time it takes to pass the inner gage of the core bit. Combining this volume of filtrate with that driven into the core while in the core barrel, results in a core that is usually totally invaded.

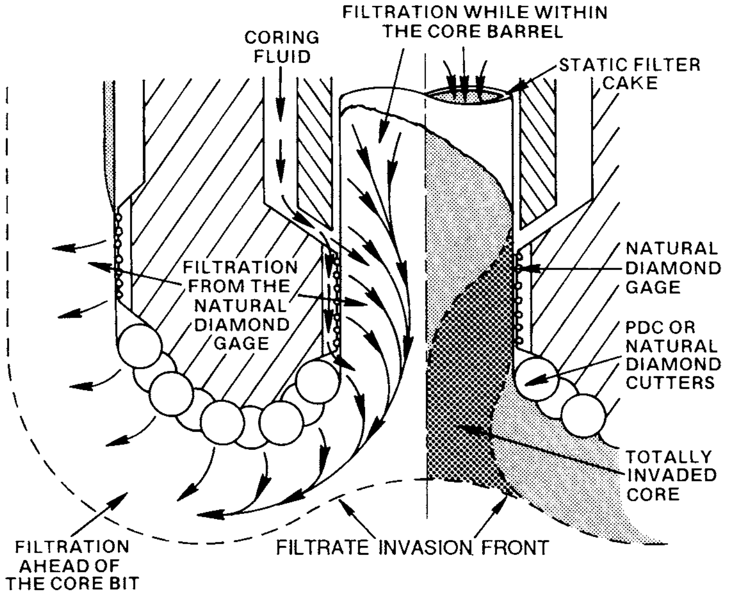


FIGURE 3. Conventional coring schematic.

Many of the problems associated with low coring rates and filtration can be minimized by the design flexibility offered by use of polycrystalline diamond compact (PDC) cutters. However, like natural diamond configurations, sporadic and/or heavy set random spacing of PDC cutters repeatedly disturbs the deposited filtercakes and allows filtrate to spurt ahead of the bit and into the formation from which the core will be cut.

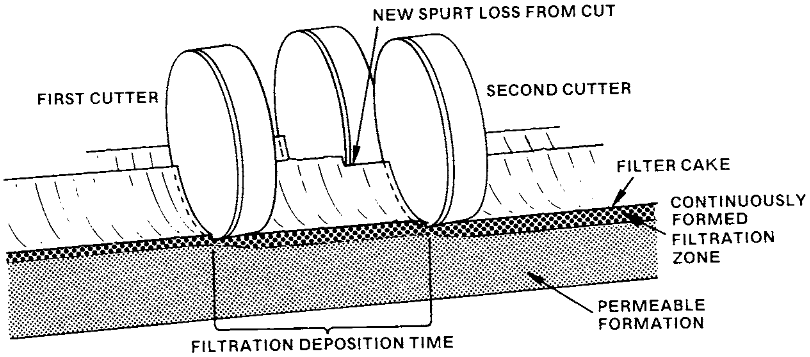


FIGURE 4. Coring with conventional bits.

Low Invasion Coring Bit Design This low invasion coring bit is designed on the basis that each cut of the rock must be deep enough to remove the filtrate spurt resulting from the previous cut. That is, the depth of cut exceeds the spurt depth. By cutting at this high depth of cut, high coring rates can be obtained to minimize the time the core is exposed to the core fluid.

The fastest coring rates can be accomplished only when the depth of cut of each cutter is below the internal filtration zone. When the depth of cut of each cutter falls *within* this zone, the formation is effectively strengthened by the added pressure gradient, and coring rates will be reduced. By cutting below this zone, the cutters encounter the formation in what is essentially a pressure balanced condition. The literature supports that coring and drilling rates can be increased significantly by cutting in a pressure balanced state, *i.e.*, where the pore pressure gradient is not elevated in the proximity of the cutter/rock failure interface. *(Gatlin, 1960)*

By minimizing the number of cutters on the core head and arranging them into discrete rows, several key filtration parameters can be optimized, including the time for liquid phase invasion in the filtration zone.

Spacing of the rows and cutters is designed to provide the optimum time to permit immediate cessation of spurt loss to the formation, and the maximum time before the filtercake is disturbed by the next cut.

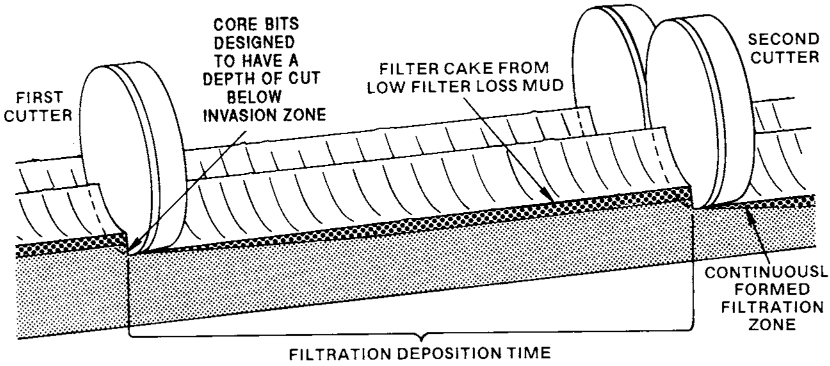


FIGURE 5. Low invasion coring.

The degree of filtrate invasion is magnified in the area where the core is sized. It is now understood that infiltration of the core is largely influenced by what happens within a small region near where the outer diameter of core is cut.

To minimize this infiltration, new core bits have been designed with a unique ID gage. The conventional natural diamond gage has been eliminated, and only a few, shaped PDC cutters are used to size the core.

The PDC gage cutters have a small flat to ensure an in-gage core while minimizing disturbance to the filter cake formed on the core surface. The core bits used for projects described in this paper contained three of these special PDC gage cutters.

The core head profile has been swept vertically and away from the core. This assures filtration by the cutters will not enter the core.

The core heads also have been designed to properly clean and cool with low mud volumes through use of large fluid courses and directed face discharge ports. (Figure 7)

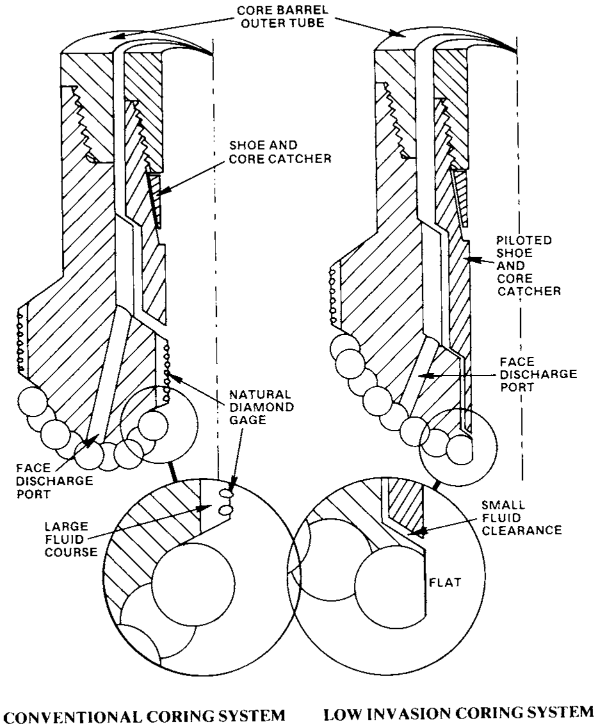


FIGURE 6. Comparison of conventional and low-invasion coring systems.

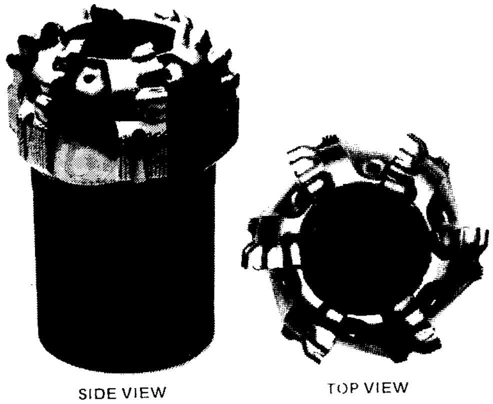


FIGURE 7. Low Invasion Core Bit (RC412 - 8-1/2" x 4")

Core Barrel Design

In this system, a special piloted core shoe is nested close to the special gage cutters. (See Figure 6.) As soon as the core is cut, it enters the inner tube of the core barrel. Once the core enters the inner tube with its relatively undisturbed and low permeability static filter cake intact, little additional filtration occurs.

The high coring rate helps reduce filtration while the core is in the barrel. As the core enters the barrel at high rates, the pressure gradient is expanded over a significantly longer distance and is no longer localized, thus reducing the already small contributions of filtrate through the static filter cake.

The special core shoe also has been designed to minimize the volume of coring fluid to which the core is exposed before it enters the inner barrel. Although the work described in this paper was completed using a standard 6-1/4" x 4" OD core barrel with the new bit/shoe design, similar systems have been designed for other specialized core barrels, including full-closure and pressure coring systems.

System Results

Figure 8 illustrates the workings of the total system.

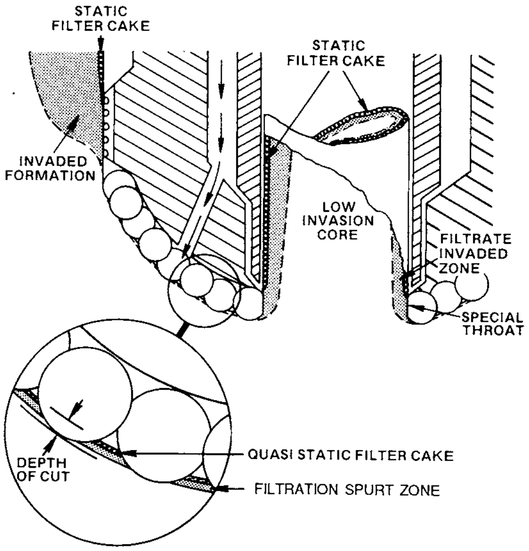


FIGURE 8. Low invasion coring system schematic.

It should be stressed that each of the components previously discussed must be used in order to take cores with low fluid invasion. The field test described in this paper and in other works near publication *(see acknowledgements)* leads to the conclusion that the schematic shown accurately represents the process taking place while coring with this system.

The low filter loss mud effectively controls filtration by forming a shallow internal filtercake at the cut surfaces, and forms a low permeability static filtercake on the core surface.

Filtration ahead of the bit is minimized by the lack of filtercake disturbance between subsequent cuts.

The profile of the core bit, in conjunction with the special ID bit gage and high coring rates, allow minimal fluid loss to the core at the most critical filtration point.

The nested pilot shoe is positioned to receive and protect the core and its "impermeable" filter cake immediately after it is cut by the shaped PDC cutters.

FIELD EVALUATION

General Procedures

The described low invasion coring system was used in Elk Hills Naval Petroleum Reserve #1 (California). The objective was to recover cores having uninvaded centers which could be used to estimate *in situ* fluid saturations behind a water flood front. The oil in the cored sand is very light (34° API) and presumably is easily flushed by invading filtrate. A state-of-the-art coring program was designed to minimize filtrate invasion and fluid flushing. The experimental scheme included use of a bland, low filter loss water base coring fluid in combination with the previously described low invasion core bit, which was run using favorable rotary speeds and penetration rates.

A total of 571 feet of 4-inch diameter core was cut in the Stevens sand section using an 8.5-inch Eastman Christensen RC412 core head and a 30-foot core barrel. Redundant bromide and iodide tracers were added to the coring fluid to track filtrate invasion.

To minimize the effects of tracer diffusion, core segments from selected depths were dissected at the wellsite as soon as possible after surfacing the core. Subsequently, fluid saturations and tracer contents were determined on each piece to evaluate depth of filtrate invasion and its effect on reservoir fluid flushing.

Core segments from 38 depths are included in the analysis. Each 2-inch core segment was dissected with an air-cooled saw as shown in Figure 9 to provide 0.5 inch resolution along the radius of the core.

Since both sides of the core are included, the dissection scheme also provides duplicate samples in the same stratigraphic layer of sand.

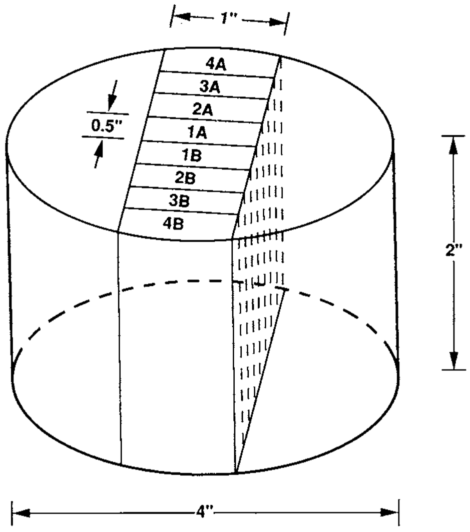


FIGURE 9. Core dissection scheme for filtrate tracer and fluid saturation study.

Coring Fluid Design

The fluid used with this low invasion coring system was a basic water base and clay fluid with good fluid loss properties. It was designed to be as bland as possible (i.e., containing minimum surface altering chemicals), and yet carry weight from 64 to 82 pcf (8.6 to 11 ppg).

The weighting requirement was necessary because of a pressure depleted upper zone and a highly pressured lower zone under active water flood.

Basic fluid composition included:

10 ppb API bentonite (prehydrated in fresh water)
6 ppb starch (w/biocide to prevent fermentation)
1 ppb polyanionic cellulose (regular viscosity)
6 ppb Gilsonite resin (blended with surfactant coating)
10.5 ppb potassium chloride
pH 8 to 8.5 (adjusted with KOH)

An objective was to design a fluid having a low static API filter loss (4 to 7 cc/30 min) and especially, a very low short-term spurt loss. This was accomplished by adding polymer and starch for liquid phase thickening, and by adding bentonite and Gilsonite for their particle plugging characteristics. Gilsonite was necessary to reduce the high temperature, high pressure fluid loss to less than 20 cc/30 min (run at 200°F to match reservoir temperature) and to provide a source of particles with a wide range in size.

Another objective was to prevent permeability damage in the core and formation. Therefore, the chloride concentration was maintained between 15,000 and 28,000 ppm with potassium chloride, roughly approximating the original electrolyte concentration of the reservoir brine.

Barite was added as required to adjust the coring fluid density to compensate for anticipated reservoir pore pressures. Prior to cutting the first core, 0.5 ppb sodium bromide and 0.2 ppb potassium iodide were mixed with the coring fluid to serve as chemical filtrate tracers.

Drilled solids control is important in minimizing filter loss; in this case, only a pair of Floline cleaners with 140/170 mesh screens and a downstream mud cleaner were necessary to keep the solids down.

No chemical thinners were required during the coring process. This is due in large part to the bit design and the high penetration rates creating relatively large chips that were not being ground into small particles, which are hard to separate from the coring fluid. This made it easy to maintain desirable fluid properties during coring, and eliminated the need for addition of undesirable chemicals that detract from the fluid's blandness.

TABLE 1. CORING RESULTS

CORE #	DEPTH IN (ft)	FOOTAGE CUT	% RECOVER	ROP (ft/hr)
1	7000	28	104	50.9
2	7028	30	100	94.7
3	7058	30	101	138.0
4	7088	21	76	89.0
5	7109	30	72	75.0
6	7139	30	98	94.7
7	7169	30	91	200.0
8	7199	30	100	200.0
9	7229	30	102	26.5
10	7259	30	100	72.0
11	7289	30	99	112.5
12	7319	30	95	163.6
13	7349	30	102	85.7
14	7379	30	100	75.0
15	7409	30	94	105.9
16	7439	30	100	128.6
17	7469	30	100	56.3
18	7499	29	92	108.8
19	7528	30	93	25.7
20	7558	13	100	17.7

SUMMARY

Total Footage Cut = 571'
Total Footage Recovered = 549.7'
Total % Recovered = 96.3%
Total Days = 10 days
Total Time = 8 hrs., 19 minutes

Average Min. per Foot = 8 min.
Average Feet per Hour=68.6'/hr.
Core Barrel = 6-1/4" x 4" x 30'
Core Bit = 8-1/2" x 4" (RC412)

Coring Procedures

Coring started with a new low invasion bit at 7000 feet. A chromed 4-inch inner barrel was run inside the 6-1/4" x 30-ft outer barrel. Eight 6-1/4" heavy weight drill pipe with jars in the middle were placed on top of the barrel. Optimum bit weight and rotary speed were determined on the first core to be 10,000 to 20,000 lbs and 100 rpm, respectively. Most of the core was cut with 15,000 lbs on the bit and at 100 rpm. Hole angle decreased from 15° to 10° from vertical during cutting of the 571 ft. of core.

Total core recovery was 96.3% and the average penetration rate was 68.6 ft/hr as shown in Table 1. From the rotary speed and spacing between screw marks on the sides of the cores, it was determined that the penetration rate for the sandstone sections ranged from about 150 to 310 ft/hr. The rate in shales was much lower, with a range from about 12 to 25 ft/hr.

The only direct comparisons available for the Stevens sandstone are those for conventional diamond bits, which had penetration rates ranging from 1.5 to 20 ft/hr, with an average of about 5 ft/hr. Apparently, the low invasion bit is capable of penetration rates 10 to 15 times faster than conventional diamond bits.

Tracer and Fluid Saturation Analysis Procedures

After dissection, the core segments were wrapped individually in several layers of food wrap, then in aluminum foil, and stored just above freezing temperature. Later, each section was individually weighed, measured, and Dean Stark extracted to determine fluid saturations and porosities. The residual core material was then dried, crushed, and extracted with 0.1 normal sodium acetate to quantitatively recover the tracers. Bromide was determined in each extract by ion chromatography, and iodide, by inductively coupled argon plasma spectroscopy. Tracer concentrations in the pore water were calculated on the basis of the determined pore water volumes. In addition, brine permeabilities were measured on each segment to determine the relationship between filtrate invasion and reservoir permeability.

Results and Dicussion Bromide tracer results shown in Figure 10 indicate that very little filtrate invaded beyond 0.5 inch into the core. Results for the iodide tracer were very similar to those for bromide.

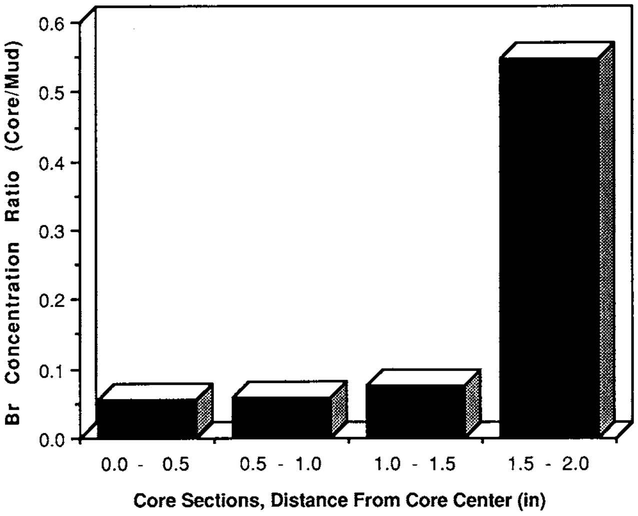


FIGURE 10. Bromide distribution in cores averaged over both sides of core at 38 different depths.

Tracer concentrations in the coring fluid varied during the cutting of the 20 cores. Therefore, bromide concentrations shown in the figures have been normalized by dividing the bromide concentration in the pore water by the bromide concentration in the coring fluid used to cut each of the respective cores.

Note that the bromide concentration in the outer 0.5 inch of the core averages only about 55% of that in the coring fluid. This means that the average depth of filtrate invasion for all 38 core samples is only about 0.25 inch into the core. An analysis of variance shows the probability of a real difference in bromide concentration among core sections is greater than 99.99%.

Figure 11 shows variations in filtrate invasion among the samples for different coring depths.

In the outer half-inch, the pore water in samples from the different coring depths ranges from about 20 to 100% displaced by filtrate. Most of the samples show no evidence of invasion beyond a half-inch. But, in core segments from three or four of the depths, there is evidence that a small amount of filtrate penetrated into the second core section.

A close examination of the tracer data for each depth shows there is usable uninvaded core material in the center of the core at each of the 38 depths included in the study.

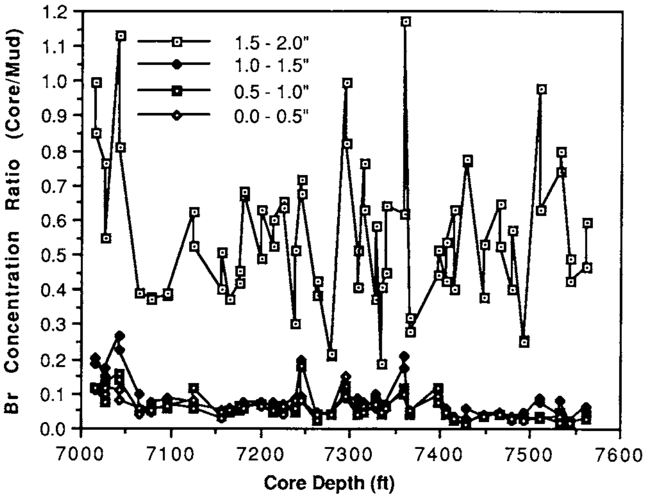


FIGURE 11. Bromide distribution in cores at different depths.

The reservoir pore water also contains some background bromide and iodide at concentrations that vary with depth, because of varying degrees of water flood sweep. It was not possible to directly determine these levels; thus, no background corrections are included in the data.

Note in Figure 10 that the two 0.5 inch sections closest to the center of the core have nearly identical low concentrations of bromide. This obviously is the average background bromide concentration in the *in situ* pore water. The concentration data are averaged over both sides of the core at each depth for 38 depths; thus, each bar in the figure represents 76 determinations.

Fluid saturations averaged over all 38 depths are shown in Figure 12. The relatively high water saturations and low oil saturations (approximately 55 and 12%, respectively) were expected because the core was cut behind a water flood front.

The gas saturations are higher than expected. This creates some problems with interpretation of fluid saturation results because of fluid expulsion from the core by expansion of gas as the core ascended during recovery.

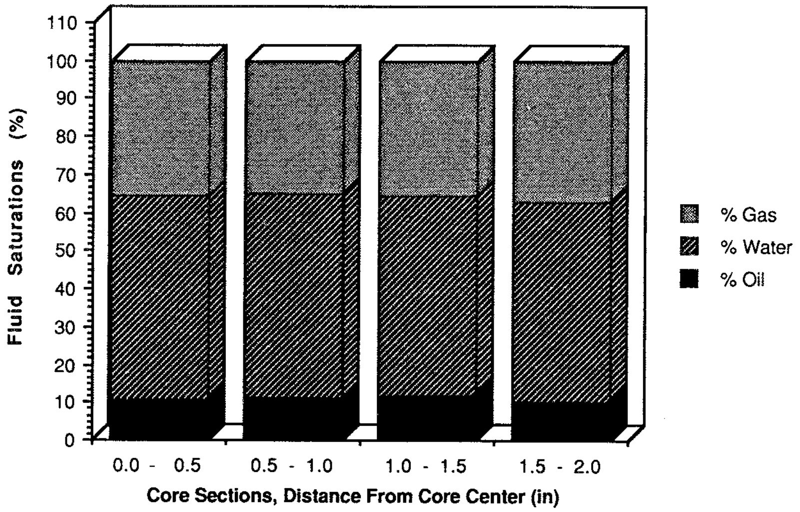


FIGURE 12. Fluid distribution in core, averaged over both sides of core at 38 different depths.

Oil saturation results, illustrated in Figure 13, show a significantly lower oil saturation in the outer half-inch section of the core than in the adjacent section. An analysis of variance shows the probability of a real difference in oil saturations among core sections is 97.4%. This observation, combined with the tracer data, indicates that the outer half-inch of the core was partially flushed by invading filtrate. Oil saturations are expressed as a percentage of the total liquid because, under reservoir conditions, the gas is probably totally dissolved in the liquids.

Except in the outer half-inch section, there appears to be a gradual rise in oil saturation from the core center toward the edge. The reason for this is not known; it may be an artifact of gas expansion during recovery of the core.

Under reservoir conditions, most of the gas is dissolved in the oil phase. As the core ascends during recovery, the pore pressure declines and gas breaks out of solution. As a result, the oil (plus gas) fraction expands, and this causes oil to preferentially move outward toward the edge of the core.

Perhaps the best estimate of *in situ* oil saturation in this case, is the average saturations of the three inside sections, weighted by their cross sectional areas.

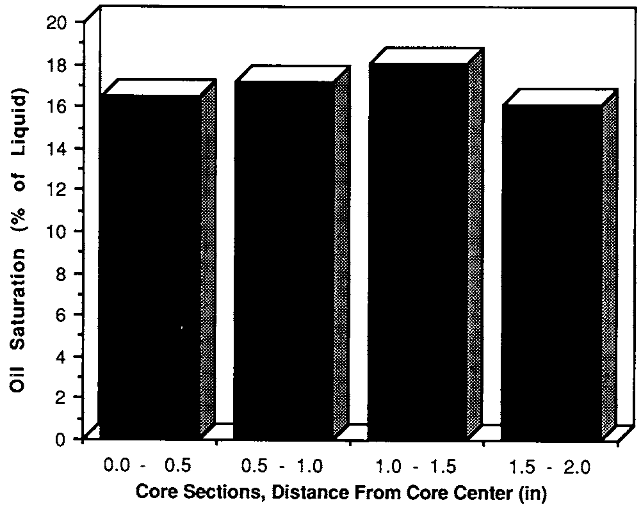


FIGURE 13. Oil saturation distribution in core, averaged over both sides of core at 38 different depths.

Plots of bromide tracer concentrations in the two outer sections plotted against permeabilities for all 38 depths are shown in Figures 14 and 15. Results indicate that filtrate invasion is not significantly related to brine permeability in this study.

Similar plots of oil saturations against permeabilities also show no relationships. Brine permeabilities of miscibly cleaned plugs from the 38 segments in this study ranged from 0.01 to 45 md. It could be risky to extrapolate these conclusions about permeability effects to other formations.

CONCLUSIONS

It is possible to obtain cores with usable uninvaded and unflushed centers using a new coring system. Success of this system in the Elk Hills field (California) is attributed to the combined use of:

(1) a new core bit, especially designed to minimize invasion;
(2) a high penetration rate with a nominal rotary speed; and
(3) a bland, low spurt-loss water base coring fluid.

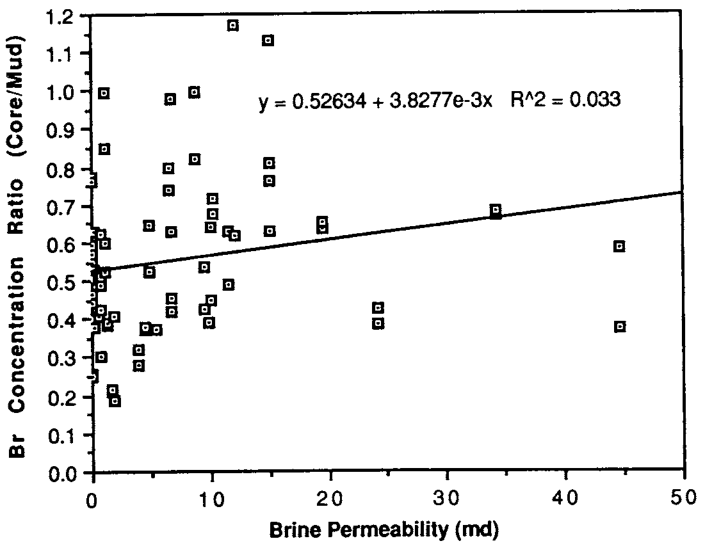


FIGURE 14. Relationship between degree of filtrate invasion in outer 0.5 inch of core and sand permeability.

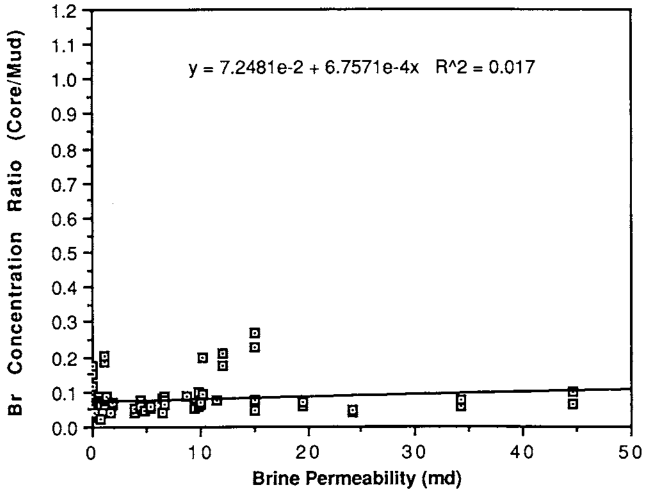


FIGURE 15. Relationship between degree of filtrate invasion 0.5 to 1.0 inch into the core and sand permeability.

The low invasion core bit is designed to minimize filtrate invasion ahead of the bit by its crown shape, cutter placement, and penetration rate capabilities. Filtrate invasion is minimized in the throat of the bit and in the core barrel by eliminating the natural diamond inside gaging surfaces, and by extending the shoe to minimize the time of the core's erosive contact with the flowing fluid.

Results from the Elk Hills field evaluation are as follows:

1. All 38 cores analyzed in the study had usable centers that were uninvaded and unflushed by coring fluid filtrate.
2. Average filtrate invasion distance was about 0.25 inch into the core, with very little filtrate invading beyond 0.5 inch.
3. There was no evidence of pore fluid flushing beyond 0.5 inch into the core.
4. The new low invasion core bit is capable of cutting cores at a very high rate of penetration (up to 310 ft/hr) in Stevens sandstone.

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SI CONVERSIONS

in	x	2.540	E + 01	=	cm
ft	x	3.048	E - 01	=	m
Bbl	x	1.589	E - 01	=	m^3
°F	x	(°F - 32)/1.8		=	°C
US gal/min	x	6.309	E - 02	=	dm^3/s
lbf	x	4.448	E + 00	=	N
lbm	x	4.536	E - 01	=	kg
lbm/US gal	x	1.198	E + 02	=	kg/m^3
psi	x	6.895	E + 00	=	kPa

NOMENCLATURE

ppg - pounds per gallon
ppb - pounds per barrel
pcf - pounds per cubic foot
API - American Petroleum Institute
ppm - parts per million
KOH- Potassium Hydroxide
RPM- Revolutions Per Minute
p - differential pressure
md - millidarcy