AADE-02-DFWM-HO-36

Real Time Imaging in Invert Emulsion Fluids – Is It Now a Reality?

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This paper was prepared for presentation at the AADE 2002 National Drilling Conference, "Drilling & Completion Fluids and Waste Management", held at the Radisson Astrodome in Houston, Texas, April 2-3, 2002. This conference was hosted by the Houston Chapter of the American Association of Drilling Engineers. The information presented in this paper does not reflect any position, claim or endorsement made or implied by the American Association of Drilling Engineers, their officers or members. Questions concerning the content of this paper should be directed to the individuals listed as author/s of this work.

Abstract

Advancements in electrical imaging tool technology and in data capture and transfer have allowed the development of systems designed to give an image of the wellbore in real time. Obtainable information from these downhole tools varies from thin-bed analysis, fracture identification and dip data, to geo-mapping to allow effective geo-steering and geo-stopping. This translates to less trouble time and faster well-data processing turnaround time, all contributing to a significant increase in efficiency. The requirement for high conductivity in the fluid has meant that historically this niche has been reserved for water-based drilling fluids.

A revolutionary re-engineering of invert emulsion drilling fluids has resulted in an invert emulsion fluid with conductivity levels of water-based fluids. This fluid brings the innate advantages of invert emulsions (wellbore stability, shale inhibition, lubricity, filtration, thermal stability, solids tolerance) to further improve drilling efficiency. This unique fluid opens up the frontiers of real-time data collection into more complex well designs, where the use of invert emulsion fluids is desirable from an economic and risk minimization standpoint.

In this paper the authors will discuss the equipment, data transfer and fluid requirements needed to achieve the goal of real-time imaging in invert emulsion fluids. Results from the recently developed, highly conductive invert emulsion fluid will be presented, showing how this is synergistic with the tool and data transfer requirements.

Introduction

The acquisition of finely detailed formation imaging logs is an increasingly critical component in fully evaluating the potential of a field prior to the development phase. The analysis of these images allows recognition and quantification of geological features, such as orientation and type of fractures and faults, gives information on geological deposition, and may be used to optimally locate the zone where the reservoir will be perforated to maximize hydrocarbon production. In addition to this, achieving high-quality images in a real-time manner would allow improved well planning to be carried out to optimize well placement, and can give additional information related to wellbore stability.[1]

Resistivity imaging devices are normally the instruments of choice in defining geological features because of their inherent high-resolution capability and the wide dynamic range of the formation properties which can be measured. Such devices function by sending an alternating current radially out from one or more electrodes into the formation (Fig. 1). The current returns via the drilling fluid column to the metallic housing of the tool. This technique requires the presence of a current path through the drilling fluid and any filter cake which may be present between the electrodes and the borehole wall. With wireline (or tubing-conveyed) micro-resistivity logs, the electrodes are present on a series of pads which are pressed into contact with the borehole. Resistivity-at—bit-while-drilling devices, used for geostopping and geosteering also rely on electric current transmission from the bit to the formation. Imaging-while-drilling techniques have the electrodes present in the perimeter of a stabilizer which is offset from the borehole wall (Fig. 2). In each case the tool performance is optimized for a low-resistivity fluid system.

In water-based drilling fluids (WBM), the resistivities of the fluid, filter cake and filtrate are low because of the naturally high conductivity of water and, to a greater extent, saline solutions. Because high conductivity provides relatively unrestricted current flow from a logging tool, signal response from the formation is generally of the highest quality when using WBMs.

Conversely, conventional oil-based fluids (OBM) are designed to provide oil-wet surfaces and water-free filtrates. These fluids consist of an internal brine phase that is strongly emulsified into a non-polar oil phase. Thus, the fluid, filter cake, and filtrate are non-conductive and block the flow of electrical current. Consequently, responses from resistivity logging tools in conventional OBM are poor or non-existent.[2]

Achieving usable wellbore image logs and resistivity-at-the-bit measurements when using oil-based drilling fluid systems has been historically almost impossible due to the electrical insulation properties of these fluids. Conversely, drilling objectives and other performance criteria often prohibit the use of water-based fluids, which are capable of delivering such high-resolution logs. Azimuthal borehole images in oil-based mud systems are commonly delivered by wireline conveyed ultrasonic measurements, or by while-drilling conveyed azimuthal density measurements. Higher resolution images are generally out of reach in oil-based systems since the measurement technology requires a low-resistivity fluid path.

The development and successful application of a conductive oil-based drilling fluid system that produces water-based logging quality and enhanced geo-steering, without sacrificing the performance advantages of an invert-emulsion fluid is described below. The unique system, which represents a leap forward in fluid technology, exhibits an electrically conductive continuous phase that yields a high-performance fluid in conjunction with a conductive mud, cake and filtrate.

Research and Development

Conductivity of a typical salt-containing water-based drilling fluid is commonly more than one million times higher than that of typical oil-based fluids. The conductivity of invert emulsion fluids increases with decreasing oil-water ratio (OWR) and with increasing tool frequency. However, in both cases the effect is minimal. This indicated a novel solution being required to increase OBM conductivity to a level adequate for efficient resistivity logging. Based on modeling work and knowledge of the tool designs, a target conductivity of ~10,000 microSiemens/m was set for a conductive oil-based fluid (COBM) for wireline resistivity logging, and a target of ~50,000 microSiemens/m was set for resistivity-while-drilling measurements.

Many routes to achieving a conductive OBM were investigated with initially little success. These included the incorporation of a micro-emulsion (too sensitive to temperature and chemistry changes), use of electrically conductive solid particles (high risk of screening out the conductive particles), and formulation of invert muds of border-line stability (extreme difficulty in maintaining a stable fluid during the drilling process).

The most obvious, but chemically most difficult, approach was to incorporate appropriate additives to make the continuous oil phase conductive. For logging purposes, this option had the advantage of producing a conductive filter cake and filtrate. Thus, this route was chosen for the final development of a newly formulated COBM. A number of patent applications were filed during this development process resulting in several patents.[3-4]

The initially developed method relied on dissolving a specific ionic material in the oil phase that was able to dissociate into a mobile charge-carrying species, thereby making the continuous phase conductive. To achieve this process, the polarity of the continuous oil phase was firstly altered by addition of a polar solvent, and the mobility of the ionic material was boosted by incorporation of a specific oil dispersible surfactant.

Inorganic ionic additives generally exhibit much higher solubility in water than in 'oils' and as such were not applicable for use in a COBM. The ionic additive must have a preference for partitioning into the oil phase, particularly as temperature (and thus ionic mobility) increases. In addition, the additive chosen should not exhibit a high degree of surface adsorption characteristics due to the high solids surface area commonly present in OBM. After some searching, a series of organic nitrogen compounds were found which met the partitioning and surface adsorption characteristics required, and these chemistries were fine-tuned through laboratory formulations and testing to select the optimum molecule that was capable of dissociation in the polarized organic liquid phase.

The choice of solvent was easier in that any liquid with good polarity and relatively low water solubility should be applicable. Acceptability of the solvent in terms of elastomer compatibility, environmental, health and safety characteristics, and flash and pour points were other criteria considered. The solvent chosen for the COBM is a mixture of glycol ethers with low water solubility.

As anticipated, the newly formulated COBM exhibited a conductivity that was proportional to temperature, thus downhole logging temperatures would assist in ensuring that the drilling fluid imparted conductivity sufficient to generate good log response. To further boost the conductivity properties of the fluid both at low and elevated temperatures, and to reduce the relative concentrations of solvent and organic salt required, investigation into the effects of co-surfactants was initiated. The introduction of a compatible co-surfactant allowed improved oil-phase solubility and mobility of the organic salt – resulting in greater conductivities at lower salt and solvent concentrations. The co-surfactant also contributed to low-temperature conductivity by being preferentially soluble in the polar oil phase at temperatures <60°C. The relationship between conductivity and temperature for the initially developed COBM is shown in Fig. 3.

The ultimate test for both additives was their ability to produce a stable drilling fluid with relatively high conductivity, good rheology and HTHP fluid loss, and high contamination tolerance. In order to allow adequate flexibility in controlling rheology and fluid loss, the conductive formulations were prepared with products normally utilized in a conventional OBM. The formulations were also optimized for tolerance to various contaminants, as well as imparting shale inhibition and the other properties expected of an invert emulsion drilling fluid. The performance of this fluid both in the laboratory and field is outlined in a separate paper.[5]

Following on from the extensive testing and initial field trials of this fluid, it was determined that sufficient conductivity for high-quality, micro-imaging logs was possible in high-resistivity formations. To obtain high-quality logs in lower resistivity (<20 ohm●m) formations, and to obtain imaging-while-drilling logs, the conductivity had to be increased. This was attempted using the existing chemistries developed for the COBM. It was soon discovered that achieving the levels of conductivity required would necessitate very high concentrations of additives. This had a detrimental effect on fluid properties and performance, as well as posing an increased health and safety risk. In addition the concentrations of additives required made the fluid economically unsuitable. A further step change in fluid chemistry would be required to achieve these higher conductivity levels.

The critical change required was to improve the mobility of the ionic species in the oil phase and to increase the charge carried through into the filter cake and filtrate. It was found that this could not be accomplished with the simpler organic salts previously tested, and custom designed molecules were investigated, showing higher oil-phase solubility and mobility. The class of chemistries finally chosen was specific charged surfactants which demonstrated low solids adsorption characteristics. These materials maintain an ionic charge whilst in the polarized oil phase by binding a molecular water layer with the surfactant molecule – resulting in a highly conductive 'organic' fluid. Typical conductivities of the initially developed fluid ranged from 75 – 2000 microSiemens/m depending on temperature. With this newly developed fluid conductivities in the range of 100,000 – 500,000 microSiemens/m were achievable. Thus the fluid exhibited the levels of conductivity that were deemed necessary for both wireline imaging and imaging while drilling through formations even of low resistivity.

Idealistic fluid conductivity requirements for micro-resistivity logs have been theoretically determined and related to anticipated response of the micro-imaging tool and the resistivity of the formations being measured. (Fig. 4). This correlation graph assumes average wellbore conditions (low levels of rugosity), filter cake thickness (~0.5 cm), and low levels of filtrate invasion. Comparing this graph to the results obtained from the initial field trial, indicated that a fluid conductivity/ formation resistivity ratio to give an estimated tool response in excess of the 3 – 4 range would allow a resistivity log of high clarity to be obtained

Application Development

As per the original COBM, further "fine tuning" of the fluid formulation was conducted. The driving force of these follow-up studies was ensuring optimal drilling performance could be achieved without compromising the designed levels of conductivity required for optimal logging. During this initial testing, it was observed that long-term mixing of the fluid generated a severe drop in the conductive properties. This was further investigated, the findings being that the ionic surfactant had a tendency to react with carbon dioxide, neutralizing the ionic charge and rendering the fluid non-conductive over time. Addition of a sacrificial buffering agent which preferentially reacted with carbon dioxide resolved this problem, and conductivity properties could be maintained, even whilst exposing the fluid to a carbon dioxide gas influx. (Fig. 5).

Typical formulations for the two COBM fluids developed are shown in Tables 1 and 2. These are for 1.7-sg (14-lb/gal) fluids with an oil/water ratio of 80/20. The properties of these fluids after heat aging at 250°F for 16 hours are shown in Table 3.

Testing of the developed drilling fluid formulation was conducted over a range of fluid densities (1.1 – 2.0 sg). The fluid was also formulated in a range of base oils, including diesel, mineral oil and synthetic materials (olefin and paraffin). The stability to a variety of fluid contaminants (drill solids, seawater, cement) was examined. The results indicated that like the initially developed COBM, the fluid could be readily engineered to perform as an effective invert emulsion fluid, while maintaining the higher levels of conductivity required for enhanced logging response. Fig. 6 shows the effect of contaminations on the properties of a 1.45-sg (12-lb/gal) 80/20 OWR conductive fluid. Fig. 7 shows the effect of these contaminations on the conductivity. Table 4 shows the properties of a 14-lb/gal COBM fluid after ageing at various temperatures up to 300°F.

During this development phase, it was observed that high water-phase salinity levels became detrimental to the conductivity of the fluid. Upon further investigation – calcium chloride levels of up to 30% by weight in the internal phase could readily be accommodated without loosing the conductive properties. Above this level, conductivity was seen to rapidly decrease. (Fig. 8). It was theorized from these measurements, and from knowledge of the conductive mechanism, that salinity levels in excess of a 30% calcium chloride equivalent were sufficient to remove the molecular water layer from the charged surfactant – thus effectively changing the ionizable charge on the surfactant molecule and reducing the fluid conductivity.

Shale inhibition was an initial concern of these fluids and this was tested on a number of outcrop and field shales using traditional laboratory inhibition test methods.[6] The results of these tests are shown in Figs. 9a-d. The outcrop shale substrates used spanned the range from highly swelling (*Wyoming bentonite*) to highly dispersive (*Arne Clay*), and included two mixed shales (*Foss Eikeland* and *Oxford Clay*). Field shales from the areas of the initial field trials (blackstone shale from Canada, and tertiary clay from Malaysia) were tested prior to field tests.

Similar to the initially developed fluid, the correct selection and concentrations of emulsifier and wetting agent are critical to the successful performance of the new COBM. Due to the conductive nature of the continuous phase of the COBM, traditional electrical stability measurements for emulsion stability are no longer relevant. Monitoring of HTHP fluid loss trends, and particularly the presence of any water traces in the HTHP filtrate, are used to determine stability of the fluid. The lower the HTHP fluid loss (thinner filter cake and less filtrate invasion), the better response would be expected from the micro-image logs. Accordingly, the COBM was formulated for minimum filtration, by optimizing emulsifier levels, using an oil-swellable polymeric additive and optimizing the size distribution of bridging additives to the formations being encountered.

Further testing was carried out to compare lubricity to conventional OBM. As shown in Fig. 10, the tests showed no difference between the two. Based on these and numerous suites of laboratory tests, the final composition of the new COBM was determined that ostensibly would deliver drilling performance identical to a standard OBM.

Confirmation of the conductive properties of the COBM under elevated temperature and pressure was determined using a custom designed HTHP conductivity cell. To further ensure adequate conductivity was present under the dynamic fluid-flow conditions experienced during logging while drilling, the HTHP conductivity cell was further modified to allow the fluid to be stirred whilst measuring conductivity under HTHP conditions. The components of the modified cell are shown in Fig. 11.

Threshold concentrations of 15 lb/bbl of the solvent and 12 lb/bbl of the charged surfactant proved necessary to generate conductivity in the oil phase. The conductivity of the new COBM then remained at levels >80,000 microSiemens/m over a temperature range of 35 – 300°F. Increasing the concentrations of the conductive additives above the initial threshold level showed only marginal increases in conductivity. The conductivity response of the newly formulated COBM to increasing temperature is shown in Fig. 12, compared to the response obtained from the original COBM. Further studies into the conductivity and its maintenance in the fluid system, highlighted the importance of maintaining a concentration relationship between the emulsifiers/oil-wetting components and the conductivity additives. The actual product ratios required were dependant upon the fluid density and oil/water ratio selected, as well as the base fluid chosen.

The extensive studies completed in the research and development phases of the project, and continued through the application stages, confirmed that the formulated COBM could provide OBM-like stability, properties, and overall performance. Further, the tests suggested it would likewise provide conductivity sufficient to allow the acquisition of high-quality electrical images both by wireline micro-resistivity logging and by imaging-while-drilling techniques. Based on all of these tests, certain limitations as to system performance and application were set, and an initial engineering guidelines manual was produced for system control under field use. The following limitations were set.

a) Temperature range of 40 – 300°F
b) Density range 8.5 – 16 lb/gal
c) Salinity range 20 – 28% wt $CaCl_2$ in water phase
d) OWR range 70/30 – 85/15

Field Testing

The true test of the success of any fluid development is an evaluation of the fluid performance over a range of operating parameters and areas during drilling. To date the newly developed COBM has been used in the drilling and logging of three hole sections. The initially developed COBM was tested on two wells in the North Sea where micro-resistivity logging was carried out (Figs. 13 and 14). The actual drilling and logging results from these three wells will be the subject of a further publication and as such are not discussed in detail here.

The Initial field trial of the new COBM was held on a land well in the foothills of the Canadian Rockies, the fluid being used to drill through shallow silts/clays and the tectonically stressed blackstone shale. Imaging-while-drilling measurements were made (Fig. 15) through the upper part of this 8¾-in. section, confirming the suitability of the fluid for this logging technique.

The second and third field trials were conducted offshore Malaysia, drilling directional 8½-in. hole sections through highly reactive shales, sands, silts, and coals. In these wells high-quality micro-resistivity logs were required for a more full evaluation of the depositional environment of the field. Due to wellbore stability and logging tool issues, the initial well was completed without a successful log being obtained. The log obtained from the second well is under evaluation at the time of publication of this paper.

These logging results all indicate that the developed COBM fluids are capable of allowing WBM-quality resistivity logs to be obtained in an oil-based mud environment.

From a practical standpoint, the newly developed COBM has proven to be easily and rapidly mixed both in shore-based fluid plants and at the rigsite. The engineering control of the fluid does require considerable more attention than with a conventional OBM, however as lessons were learnt through the field application of this system, guidelines and field tests to improve the information gathered from the system, and to enhance the easy of engineering control have been developed.

Conclusions

The development of the initial COBM struck an effective balance between the optimal drilling performance of an OBM and high-quality resistivity logging previously only acquired with WBM systems. With the advent of the new COBM, high-quality resistivity logging can now also be obtained in lower resistivity formations. In addition the new COBM opens up the availability of resistivity imaging-while-drilling measurements being obtainable whilst achieving the drilling performance anticipated from an OBM. Maintaining the advantages of an OBM, with respect to fluid stability, tolerance to contamination, high levels of lubricity and low filtration were demonstrated in the laboratory and verified in the field.

The high quality of formation imaging and detailed geological interpretation that can be achieved with formation micro-resistivity logging in WBM has been demonstrated to be achievable with COBM. Resistivity-at-the-bit measurements, which can affect improved geo-steering, were demonstrated to be obtainable, along with resistivity imaging while drilling – providing the possibility of real-time advanced geological interpretation while drilling with OBM performance.

Acknowledgements

The authors thank Mary Dimataris for her help with the manuscript and M-I for permission to publish this paper. The assistance of Schlumberger drilling and measurements must also be acknowledged, as without their support and specialized knowledge this development could not have been successfully taken to the field trial stage.

References

1. Ewanek, J, and Young, S.: "Hitting Your Foothills Target the First Time," Paper CADE 2001-07, CADE Drilling Conference, Calgary, Alberta, October 23-24, 2001.
2. Mercer, B., et al.: "Detect Fractures When Drilling With Oil-Based Mud," *Petroleum Engineer International* (Sept 1994) 31.
3. Patel, A.D.: "Conductivity Medium for Open Hole Logging and Logging While Drilling," US Patent No. 6,029,755 (Feb. 29, 2000).
4. Schlemmer, R.P. and Schulz, J.F.A.: "Electrical Well Logging Fluid and Method of Using Same," US Patent No. 6,006,831 (Dec 28, 1999).
5. Laastad, H., Haukefaer E., Young, S., Tehrani, A., Delaunay, P., Feather, K., Phillips, J., and Marca, S.: "Water-Based Imaging and Resistivity Logging in Oil-Based Drilling Fluids – Today's Reality," SPE 62977, 2000 SPE Annual Technical Conference, Dallas, October 1 – 4, 2000.
6. Patel, A., Stamatakis, E., Friedheim, J.E., and Davis, E.: "Highly Inhibitive Water-Based Fluid System Provides Superior Chemical Stabilization of Reactive Shale Formations," AADE-01-NC-HO-55, 2001 AADE Drilling Conference 'Drilling Technology – The Next 100 Years,' Houston,Mar 27-29, 2001.

Table 1 Typical Composition of Initial COBM		
Base Oil	(mL)	162
Primary Emulsifier	(mL)	13.5
Secondary Emulsifier	(mL)	4.5
Lime	(g)	5.0
Polymeric filtration agent	(g)	2.5
Liquid filtration agent	(mL)	5.5
$CaCl_2$ brine	(mL)	39.0
Conductive solvent	(mL)	25.0
Conductive salt	(g)	10.0
Conductive surfactant	(mL)	6.5
Barite	(g)	350

Table 2 Typical Composition of New COBM		
Base Oil	(mL)	169
Primary Emulsifier	(mL)	8.0
Secondary Emulsifier	(mL)	4.0
Lime	(g)	5.0
Polymeric filtration agent	(g)	3.0
Alkalinity buffer	(mL)	2.0
$CaCl_2$ brine	(mL)	39.0
Conductive solvent	(mL)	18.0
Conductive surfactant	(mL)	15.0
Barite	(g)	355

Table 3 Properties after aging 16 hr at 250°F		
	Initial COBM	New COBM
Density (lb/gal)	14	14
OWR	80/20	80/20
PV (cP)	38	42
YP (lb/100 ft^2)	16	15
Gels (lb/100 ft^2)	9/12	8/15
ES (V)	26	4
HTHP (mL @250°F)	2.6	3.2
Conductivity @70°F (µS/m)	65	98,000
Conductivity @150°F (µS/m)	348	164,000

Table 4 – Porperties of New COBM Before and After Aging 16 hr				
	Initial	Aged 150°F	Aged 250°F	Aged 300°F
Density (lb/gal)	14	14	14	14
OWR	80/20	80/20	80/20	80/20
PV (cP)	36	45	42	40
YP (lb/100 ft^2)	14	16	15	13
Gels (lb/100 ft^2)	9/12	9/13	8/15	7/15
ES (V)	5	4	4	4
HTHP (mL @250°F)		3.4	3.2	4.2
Conductivity @70°F (µS/m)	75,000	89,000	98,000	95,000
Conductivity @150°F (µS/m)	125,000	140,000	164,000	165,000

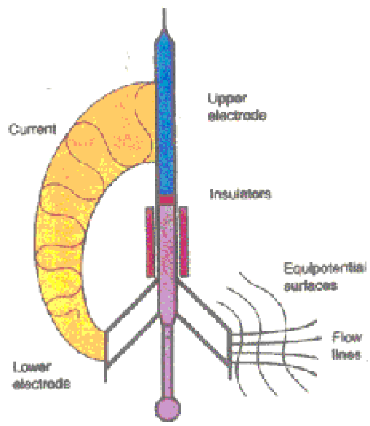

Fig. 1 –Schematic representation of layout of micro-resistivity logging tool.

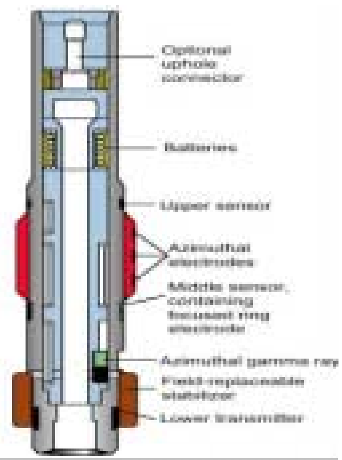

Fig. 2 – Schematic representation of layout of resistivity while drilling tool.

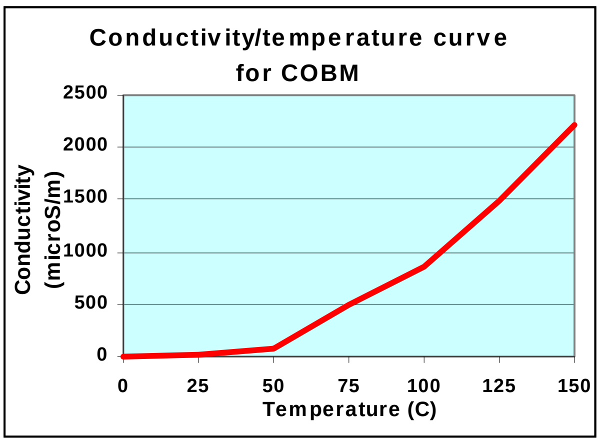

Fig. 3 – Relationship between conductivity and temperature for initially developed COBM fluid.

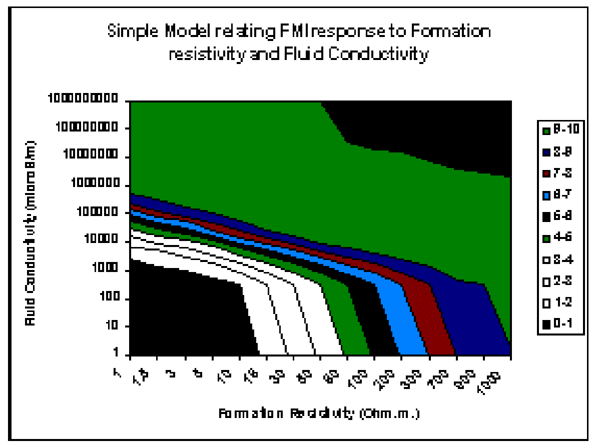

Fig. 4 –Correlation graph for anticipated micro-resistivity logging tool response.

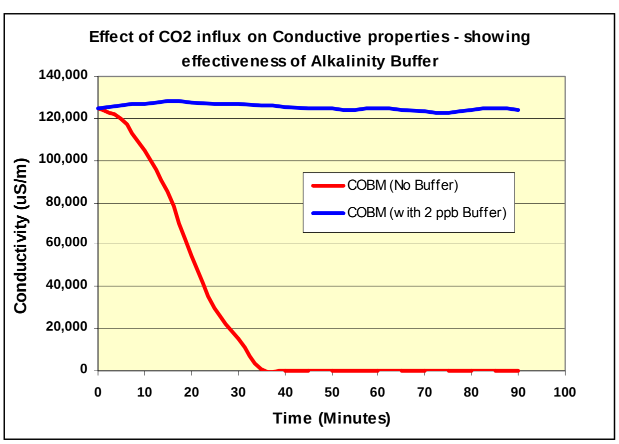

Fig. 5 – Conductivity of new COBM over time, exposed to continuous CO2 influx of 2 scf/min.

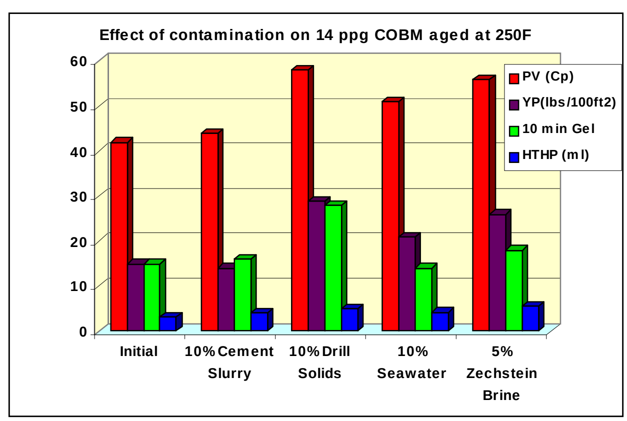

Fig. 6 – Effects of contaminants on rheological and filtration properties of new COBM.

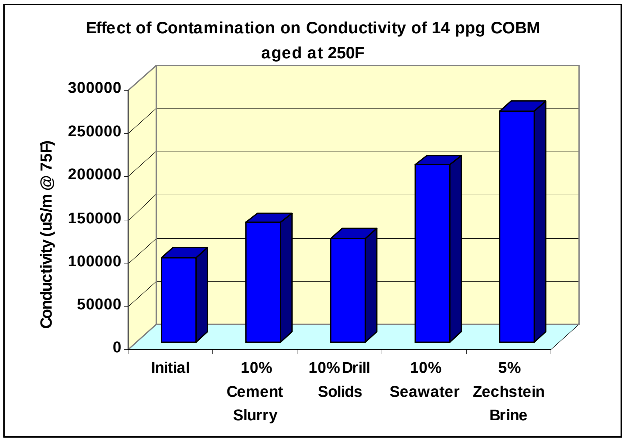

Fig. 7 – Effects of contaminants on rheological and filtration properties of new COBM.

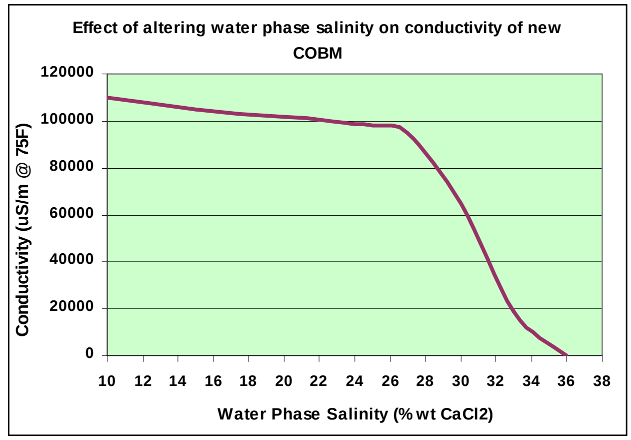

Fig. 8 – Effect of water phase CaCl2 concentration on conductive properties.

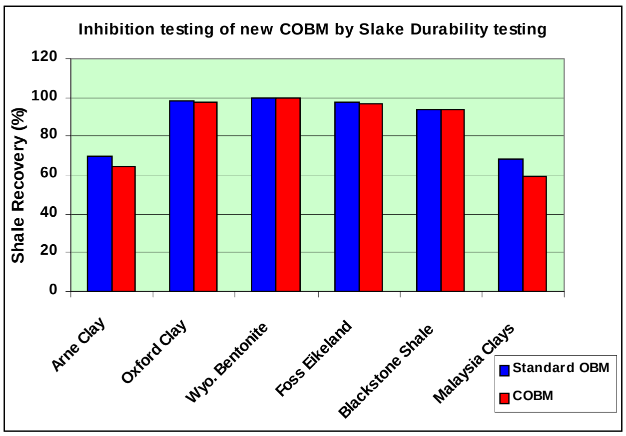

Fig. 9a – Slake durability test results from COBM development.

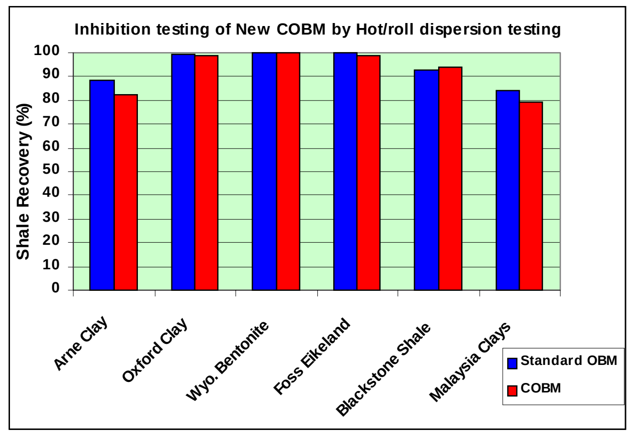

Fig. 9b – Hot roll/dispersion test results from COBM development.

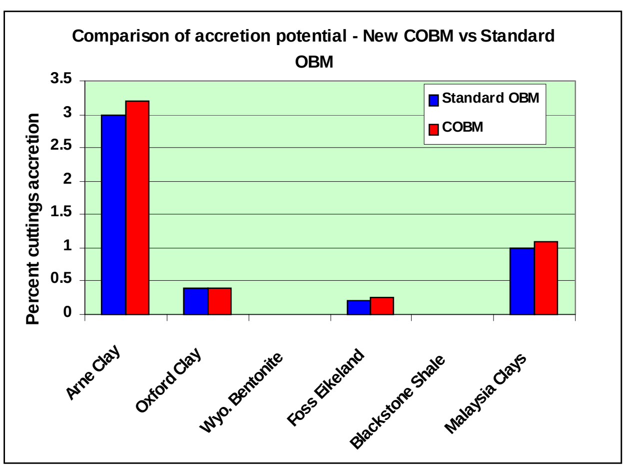

Fig. 9c – Accretion test results from COBM development.

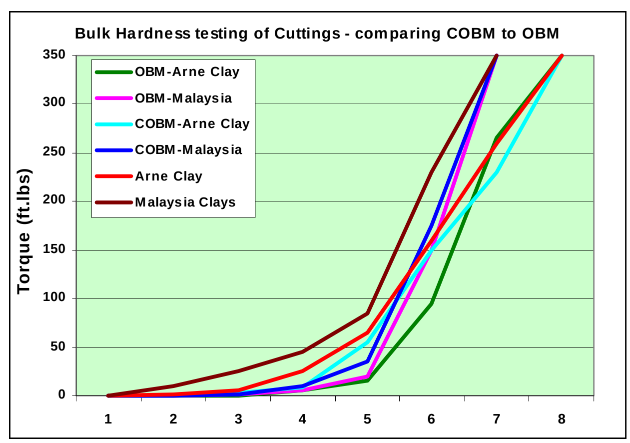

Fig. 9d – Shale Hardness test results from COBM development.

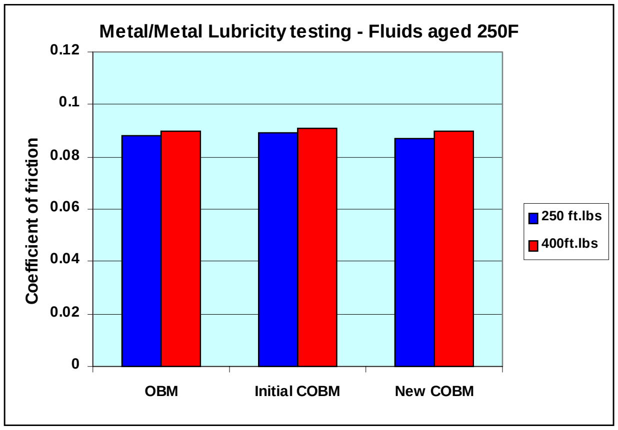

Fig. 10 – Lubricity test results from COBM development.

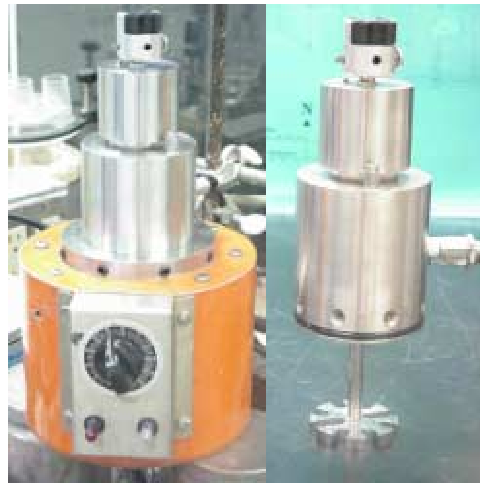

Fig. 11 – Picture of cell components developed for dynamic measurement of HTHP conductivity.

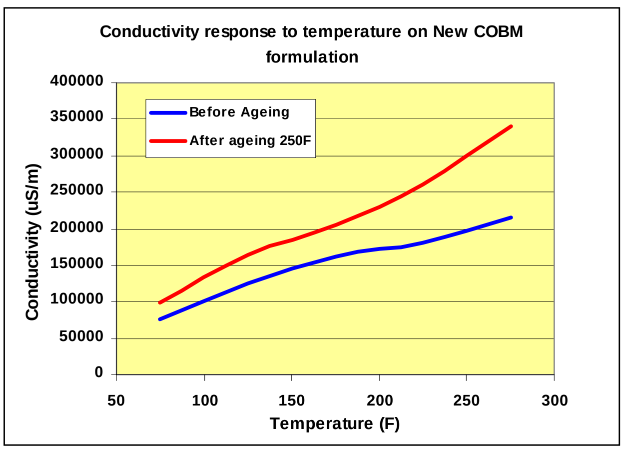

Fig. 12 – Response of newly developed COBM to temperature changes.

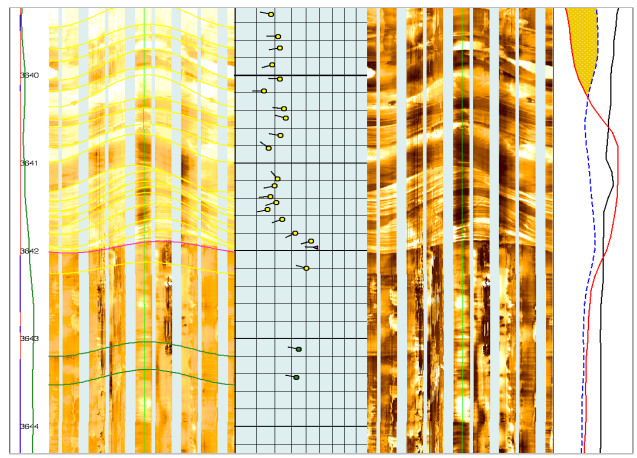

Fig. 13 – Sample of micro-resistivity log obtained from 8½-in. hole in initial field trial.

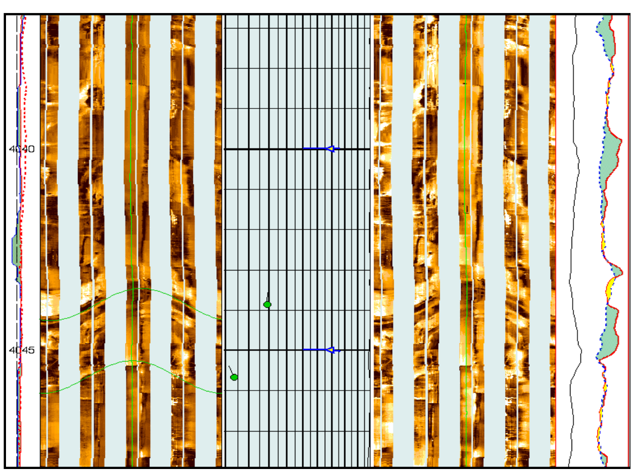

Fig. 14 – Sample of micro-resistivity log obtained from 12¼-in. hole in second field trial.

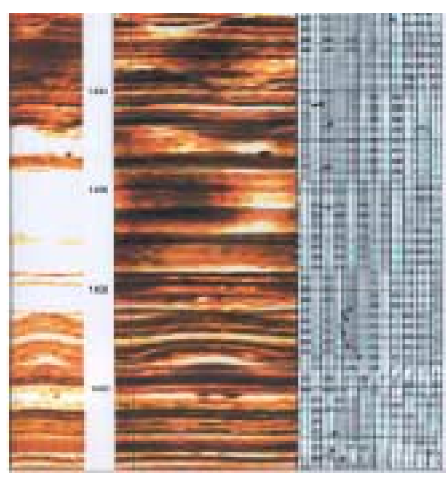

Fig. 15 – Sample of resistivity-while-drilling log obtained from first field trial of new COBM.