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Planning and Executing a Multi-National HPHT Campaign

Dominic Thomas, BG Group; Keith Anderson, BG Group; Chris Steele, Elkem; Jason McGhie, Baker Hughes; Dave Marshall, Baker Hughes

Abstract

BG planned to drill a series of High Pressure High Temperature HPHT wells in the central North Sea on both sides of the UK-Norwegian border. The technical challenges of the wells are severe but similar in all cases. In order to take advantage of this similarity, a single mud system which could be used in both countries and which met all technical and environmental requirements was needed. With expected mud weights of 18 to 19 lbm/gal and bottom hole temperatures close to 400°F, a highly stable mud system would be required. Product selection would be restricted by the need to meet the environmental criteria of both countries, thus placing some challenges on system design. A successful mud system design, meeting all of these requirements, was evaluated in the laboratory and the performance was subsequently validated in the field when Jackdaw, the first of these wells, was drilled in the UK. This well, and its side-track, were very successful from a drilling fluid and overall perspective and the same mud has been stored for use on Mandarin, the second well, in Norway. All issues with shipping mud across a national border were successfully resolved during the planning process. The mud system used contained a mixture of barite and manganese tetraoxide to ensure rheological stability during the planned extensive logging programme, in conjunction with other field-proven HPHT system components. The successful application of this system on Jackdaw has given confidence that the same fluid can be used throughout this HPHT campaign.

Introduction

In 2007 an extensive HPHT drilling campaign in the North Sea was started. The object of the campaign was the appraisal of the Jackdaw prospect and exploration drilling on prospects named Mandarin and Whitebear. All these wells have similar prognosed conditions with reservoir pressures circa 17,000 psi and undisturbed bottom hole temperatures of between 380 and 410°F. It was recognised from an early stage in the planning process that considerable efficiencies would be realised by adopting a co-ordinated approach to planning and drilling the wells to ensure that learning could be transferred from one operation to the next and that continuity of crews and service providers would enhance performance as the campaign progressed. One difficulty which threatened to make this approach unachievable was the fact that while Jackdaw and Whitebear are located in the UK sector of the North Sea, Mandarin is in Norwegian waters and therefore subject to regulation from Norway.

One of the key services on any well, and particularly HPHT wells, is the provision of the drilling fluid and associated engineering services. A contract was already in place with a service provider for provision of drilling fluids but it was felt that these wells were so far outside the normal drilling envelope in terms of their expected temperatures and pressures that it would be prudent to evaluate all available options for the wells. Therefore a strictly technical tender exercise was undertaken to choose the drilling fluid for the campaign based on fluid performance and ability to deliver engineering services under the stated conditions. To put the wells in context, Figure 1 shows the temperature and pressure of wells drilled worldwide since 2000 and where the Jackdaw well sits in relation to the spread.

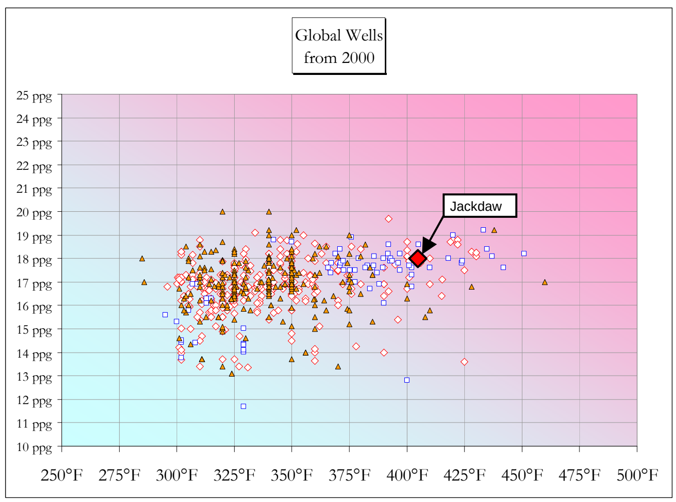

Figure 1: Jackdaw well compared to other HPHT wells

Additionally, it was stated that the fluid must be able to be used both in the UK sector and in the Norwegian sector and therefore all the proposed chemicals must have satisfactory environmental registration and classification under both regimes. Thus it was planned from the outset to be able to use the chosen fluid on both sides of the regulatory divide and realise the technical and commercial benefits from this approach. The outcome of this process was the selection of the Magma-Teq system from Baker Hughes Drilling Fluids. This system combined the proven HPHT invert emulsion technology developed for Ultra HPHT wells in the Gulf of Mexico with a weighting system composed of a mixture of conventional barite and ultrafine manganese tetraoxide (Micromax). The base oil selected for use was Escaid 120, which had satisfactory technical characteristics and was approved for use in both Norway and the UK.

Planning the Well

General Considerations

In designing the drilling fluid for the well the key considerations were to obtain a system which would be stable under the expected temperature and pressure conditions. Data acquisition was a key objective of the well and there was to be an extensive wireline logging programme requiring the fluid to be sufficiently stable to allow this to be performed efficiently. Wiper trips under HPHT procedures are extremely time consuming and therefore providing good hole conditions for logging was crucial to the success of the well. Once the fluid had been selected, detailed laboratory testing was undertaken to optimize the properties of the mud to ensure that all the well objectives could be met.

Fluid Design

The combination of high temperature and high pressure expected at the bottom of the Jackdaw well, combined with the planned extensive logging programme required a drilling fluid design which would deliver long-term stability under extreme conditions during both the drilling and logging phases of the well. Additionally, the Jackdaw well was planned as the first in a series of HPHT wells to be drilled on either side of the UK-Norwegian border in the central North Sea. Historical experience of personnel involved in the project has shown that good quality field mud always delivers greater stability and performance than fresh mud, and the fluids planning for these wells was based around creating the condition under which the specially designed HPHT fluid could be shipped across this international border and used on multiple wells. The environmental regulations in Norway and the UK are similar but not the same, especially in the way oil-based mud is handled and these considerations placed further restrictions on fluid design as not all products which would normally be considered as components of the HPHT system were acceptable under both environmental schemes.

Weight Material Selection

The basic requirements for properties of the drilling fluid were identified as shown in Table 1.

Aside from achieving thermal stability at the expected maximum temperature, the fluid's rheological profile needed to balance the contrary requirements of low viscosity to minimise equivalent circulating density (ECD) and high enough viscosity to avoid sag during both the drilling and logging phases of the well. Avoidance of gelation at high temperatures was also required to ensure a successful logging programme. For these reasons, three options for weight materials were initially considered: regular barite as the base case; manganese tetraoxide (referred to as MTO in the remainder of this paper); and a hybrid system consisting of used, HPHT field mud containing barite weighted to the required density using MTO.

Table 1. Key Drilling Fluid Properties

Property	Specification
Mud weight (SG / lbm/gal)	2.22 / 18.5
Plastic viscosity (cP)	As low as possible
100 RPM dial reading	> 25
6 RPM dial reading	> 10
HPHT filtrate (mL/ 30min) 500psi @ 428°F	< 5 on paper < 5 on 3 micron Aloxite disc
ES (volts)	> 500
WPS (chlorides)	180 – 200,000
Oil / water ratio	80/20 – 85/15

MTO was included in the design process as previous experience had shown that its small particle size (see Figure 2) and spherical shape (see Figure 3) lowers the plastic viscosity of fluids more effectively than all other readily available weighting materials[1]. It has also been shown to lower ECDs and minimise the risk of sag[2].

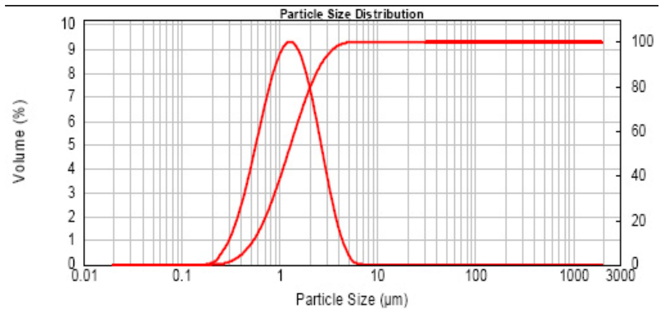

Figure 2: Manganese tetraoxide particle size distribution

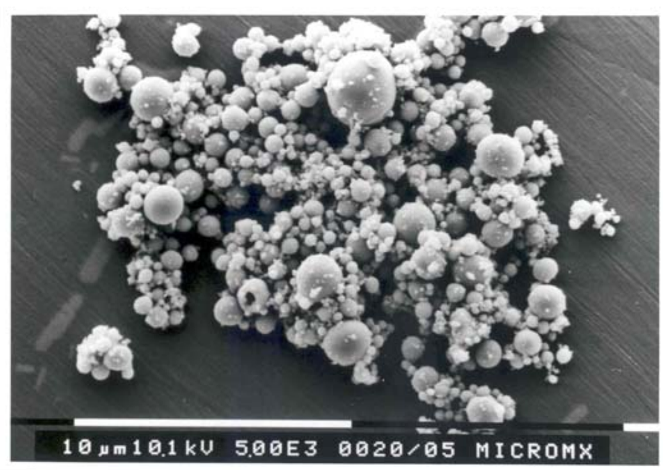

Figure 3: SEM photograph of manganese tetraoxide

Testing of the three mud systems was conducted in the laboratory to compare rheological parameters after dynamic aging for 16 hours at 428°F and static aging at the same temperature for periods of 64 and 112 hours to simulate how the mud would perform during logging runs. The results are shown in Table 2.

Table 2: Rheological Properties after Aging at 428°F

Weight Material	Rheological Property	Dynamic 16 Hrs	Static 64 Hrs	Static 112 Hrs
Barite	PV (cP)	77	91	89
	YP (lb/100ft^2)	18	25	36
	6 RPM (Dial)	7	6	6
MTO	PV (cP)	34	40	35
	YP (lb/100ft^2)	21	30	26
	6 RPM (Dial)	12	21	18
Barite/ MTO	PV (cP)	44	50	50
	YP (lb/100ft^2)	20	26	31
	6 RPM (Dial)	10	16	18

As expected, both systems containing MTO showed significantly lower plastic viscosities than the fluid weighted only with barite. Incorporation of MTO improved the shear-thinning nature of the fluid and provided elevated low shear viscosities, which were desirable for the avoidance of sag.

The fluid properties imparted by the use of MTO result from its small size (particles with a D_{50} of approx 1µm). Because of this small size MTO powders are more difficult to move pneumatically than, for example, barite. One way to achieve most of the benefits of MTO in terms of its impact on rheological parameters while avoiding the logistical issues of handling the product at the rig-site is to use both MTO and barite with the former only being handled onshore at the mud plant; this was the option selected for the Jackdaw well. This approach had the additional benefit that a mud system could be made which contained a significant percentage of fluid which had already been used to drill under HPHT conditions ,and so was "field conditioned".

Fluid Formulation

Once the decision on the weighting materials for the mud system had been made, the remainder of the design work was able to focus on achieving rheological stability at the expected maximum temperature coupled with tight control of fluid loss, the latter attribute required to ensure a thin filter-cake which would minimise the risk of logging tools becoming stuck in the open hole. The final formulation on which the subsequent well planning was based is shown in Table 3.

The base oil was chosen for its combination of low viscosity (1.98 cSt @ 40°C) and high flash point (103°C) coupled with environmental approval in both the UK and Norway. The proprietary products used in the formulation were all components of a field-proven HPHT mud system with a solid track record of previous wells, some at temperatures and pressures approaching 500°F and 30,000 psi respectively.

Table 3. Final Mud Formulation

Additive	Units	Conc'n
Seed mud (1.89SG)	Bbl/Bbl	0.535
Base oil	Bbl/Bbl	0.218
Proprietary non-ionic emulsifier	Lbs/Bbl	3.0
Proprietary secondary emulsifier	Lbs/Bbl	7.0
Lime	Lbs/Bbl	2.0
Proprietary fluid loss polymer	Lbs/Bbl	1.75
Proprietary fluid loss additive	Lbs/Bbl	3.5
MTO	Lbs/Bbl	343.0

The seed mud used had previously seen service in an HPHT well in the UK sector of the North Sea and had been exposed to temperatures up to 385°F. The oil-water ratio of this fluid was 73:27 and the internal phase salinity was 200,000 mg/L chlorides. All components of this fluid were approved for use in the UK OCNS and with the exception of one of the emulsifiers, which was classed as Red, all products were classed as Yellow in the Norwegian environmental rating system.

HPHT Rheological Stability

Detailed knowledge of the rheological properties of the fluid under downhole conditions would be required to assist with planning the hydraulics and hole-cleaning for the well, and testing was therefore conducted on an HPHT viscometer with operating limits of 600°F and 30,000 psi. A suite of measurements was made at increasing pressure and temperature combinations to simulate different points in the well. The properties of the laboratory formulated mud were very stable as shown by Figure 6. Yield point is almost constant between 250°F and 428°F and the plastic viscosity shows the expected gradual downward trend from around 40cP to around 30cP over this temperature range.

Drilling the Well

The first well undertaken in the campaign was the Jackdaw well 30/2a-7 in the central sector of the UK North Sea. The objective of this well was to appraise the prospect, which had been discovered during the drilling of the 30/2a-6 well in 2005, and to obtain a well test. As noted in the introduction, the anticipated reservoir pressure in this well was around 17,000 psi, which is equivalent to a mud weight of 17.5 to 18.5 lbm/gal. The undisturbed temperature in the reservoir was prognosed at 395-405°F. The drilling programme for the well was to drill to TD in 8½-in. hole if possible and set liner to enable the well test to be performed. During drilling it became necessary to commit to an early drilling liner and TD the well in 5 5/8-in. hole. Subsequent operations led to an equipment failure which meant that the well test could not be achieved and a decision was made to drill a sidetrack to further appraise the prospect. This was a major undertaking, re-drilling the well from the 20-in. shoe and drilling at 20° deviation to a new target. This was successfully achieved, again in 5 5/8-in. hole, with a further sidetrack in the lower section after a twist-off in the BHA, this well being referred to as 30/2a-7z,y. In total, the HPHT fluid was used in two 8½-in. and three 5 5/8-in. sections and drilled 7,889 feet over the five sections. The actual temperature seen in the wells was close to prognosis with a maximum static temperature of 386°F seen during logging operations. Mud weights of between 17.8 and 18.5 lbm/gal were required for pressure control.

Drilling Fluid Performance

The original plan in the well was to utilise the high temperature fluid formulation in the 12¼-in. section and condition the mud as drilling progressed to achieve the full HPHT specification by the 9 7/8-in. casing point, thereby ensuring a stable fluid for drilling the reservoir section. In reality unexpected weak zones in the 12¼-in. section led to the occurrence of quite severe mud losses and so it was decided to revert back to a conventional oil-based mud for this section and reserve the HPHT fluid for the later section. This approach worked well and the HPHT fluid was recovered back to the mud plant and conditioned to specification for the reservoir section. Because MTO is difficult to use in conventional bulk systems it was decided to prepare high density pre-mixes in the plant and then add barite offshore to achieve the required final density In this way the necessity to have the MTO powder offshore was negated and the necessary mix of Barite:MTO could be achieved.

In order to assess the performance of the drilling fluid, three areas were focused on: temperature stability; density behaviour; and property stability.

Temperature Stability

The most severe test for the drilling fluid in this type of well is after prolonged periods of inactivity when a portion of the fluid is exposed to the static bottomhole temperature for an extended period without circulation or the opportunity for treatment. Upon resumption of circulation the fluid from bottoms up is often seriously degraded and requires extensive re-conditioning. The HPHT fluid in use here did not exhibit any severe effects of this nature and the only evidence of any deterioration in properties was a modest increase in viscosity of the bottoms up mud, which was able to be incorporated into the active system without any detrimental effects and no extensive treatments. A typical example of this was seen on the second sidetrack 5 5/8-in. section when it was decided to deepen the well after running wireline logs. Despite being static in the well for a total of 12 days at around 385°F, the fluid when circulated out did not show any signs of deterioration and required minimal treatment. Hole conditions for the extended logging programme were extremely good and the formation evaluation specialists commented favourably on the quality of the well bore delivered by the drilling team.

Density Behaviour

The occurrence of weighting agent "sag" leading to density fluctuations is a major cause of non-productive time on HPHT wells. The mix of barite and MTO was specifically chosen to mitigate the occurrence of sag and the expected performance was borne out in practice in the field. The density of the fluid was extremely consistent after trips and during periods of prolonged slow circulation. Mud weights were monitored very closely during drilling and when breaking circulation after static periods in order to capture any density variations and provide evidence that the fluid was stable. Figure 4 shows the density of the system monitored after two trips and it can be seen that there was very little variation in returning mud weight.

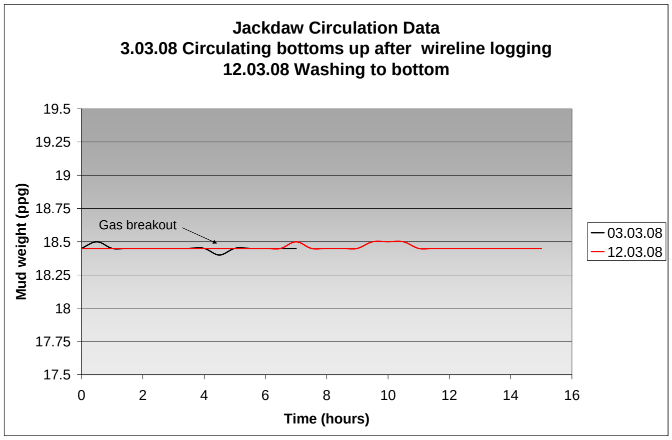

Figure 4: Mud density data after static periods

Further evidence of the stability of the system was gained from the wireline logging data. Figure 5 shows the hydrostatic profile in the well over a ten-hour period recorded by the MDT log.

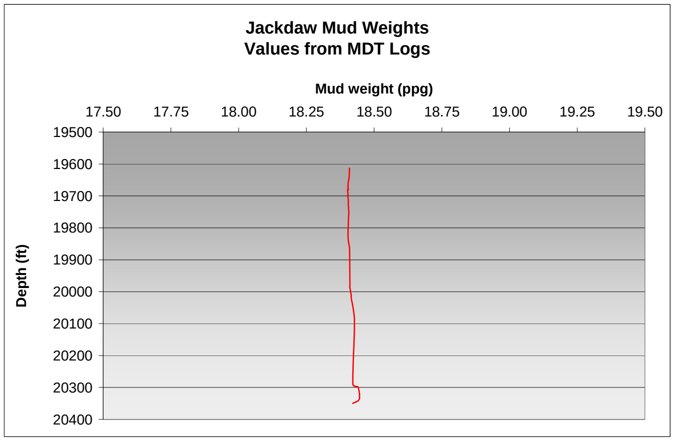

Figure 5: Hydrostatic well profile from MDT log

The fluid density was constant over the period indicating that the mud was stable under the downhole conditions. During the entire drilling operation when the fluid was in use there were never any concerns from the offshore team regarding the density behaviour of the fluid. This was despite the occurrence of several well control incidents requiring long periods of slow, controlled, circulation and it was felt that the stability of the mud system contributed positively to the ability of the drilling team to control the well safely.

Property Stability

Mud properties were closely monitored during the drilling of the wells and plotted on a daily basis. Again, the system was extremely stable and the rheological and other key mud properties were kept within specification despite the extended duration of the sections. Figure 7 shows properties plotted against time for the 5 5/8-in. sections of the z and y sidetracks and this demonstrates the long-term stability of the system. The chart shows the mud properties over a period of 71 days in the well and during this period the PV, YP and gel strengths all remained easily controllable and within acceptable limits.

Hydraulics Modeling

The management of ECD was critical on this well due to the extremely narrow margin between the pore pressure and the fracture gradient (<1 lbm/gal). As much use as possible of a downhole pressure tool was made; however these tools are at the limit of their operating envelope at the circulating temperatures encountered. Extensive hydraulic modeling was carried out using the Presmod dynamic HPHT simulator software and ECD was predicted and compared to the data obtained from the downhole tools. By doing this when data was available, sufficient confidence was gained in the modeling to allow it to be used when tool failure occurred to allow drilling to continue. The chart in Figure 8 shows the good correlation between the modeled output and actual tool data.

Wider Campaign Issues

Following the conclusion of drilling activity on the Jackdaw well in late 2008, the dedicated HPHT mud was returned to Aberdeen where it was stored until October 2009 when it was transferred by boat to Stavanger. At the time of writing, this mud has been conditioned for use on the Mandarin well in the Norwegian block 1/3. The well spudded in December 2009 and the HPHT fluid is expected to see active service in the lower sections of this well in early 2010. The planning of the Mandarin well included many personnel who had been closely involved in the Jackdaw well, both from the mud company and operator, and the senior offshore mud engineers on Mandarin also worked on Jackdaw. In other words, the initial steps in achieving the key objectives of transferring knowledge, personnel and the HPHT drilling fluid from well to well during this campaign have been achieved.

Conclusions

In the planning stages of this campaign the primary objective was to design a drilling fluid which would be stable at the extreme conditions expected in the wells. In addition to this it was also a desire to have a fluid which could be transferred between wells to derive the economic benefits accruing with re-use of the fluid in more than one section. The fact that the wells were to be drilled in different countries with different regulatory regimes was a challenge in this respect. The extensive laboratory work undertaken produced a fluid which satisfied all the requirements and proved in the field to be stable both in terms of property and density stability. This was proven on the Jackdaw well where operations extended well beyond those originally planned and the fluid remained in good condition for a greatly extended period of time in the well due to the unplanned sidetracks. The formulation also contained only products which were suitable for use both in Norway and the UK and so achieved the goal of a transferrable and re-useable mud for the campaign, which has been demonstrated by shipping the mud to Norway for the Mandarin well. The Jackdaw well also allowed the hydraulics software package that was in place to be evaluated and provide confidence in the modeling both for planning and operational purposes.

Acknowledgments

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Nomenclature

Bbl	= *Barrel*
BHA	= *Bottomhole assembly*
cP	= *centiPoise*
cSt	= *centiStokes*
ECD	= *Equivalent circulating density*
HPHT	= *High-pressure high-temperature*
lb(s)	= *Pound(s)*
MDT	= *Modular formation dynamic tester*
MTO	= *Manganese tetraoxide*
OCNS	= *Offshore chemical notification scheme*
lbm/gal	= *pounds per gallon*
psi	= *pounds per square inch*
PV	= *Plastic viscosity*
RPM	= *Revolutions per minute*
SG	= *Specific gravity*
TD	= *Total depth*
YP	= *Yield point*

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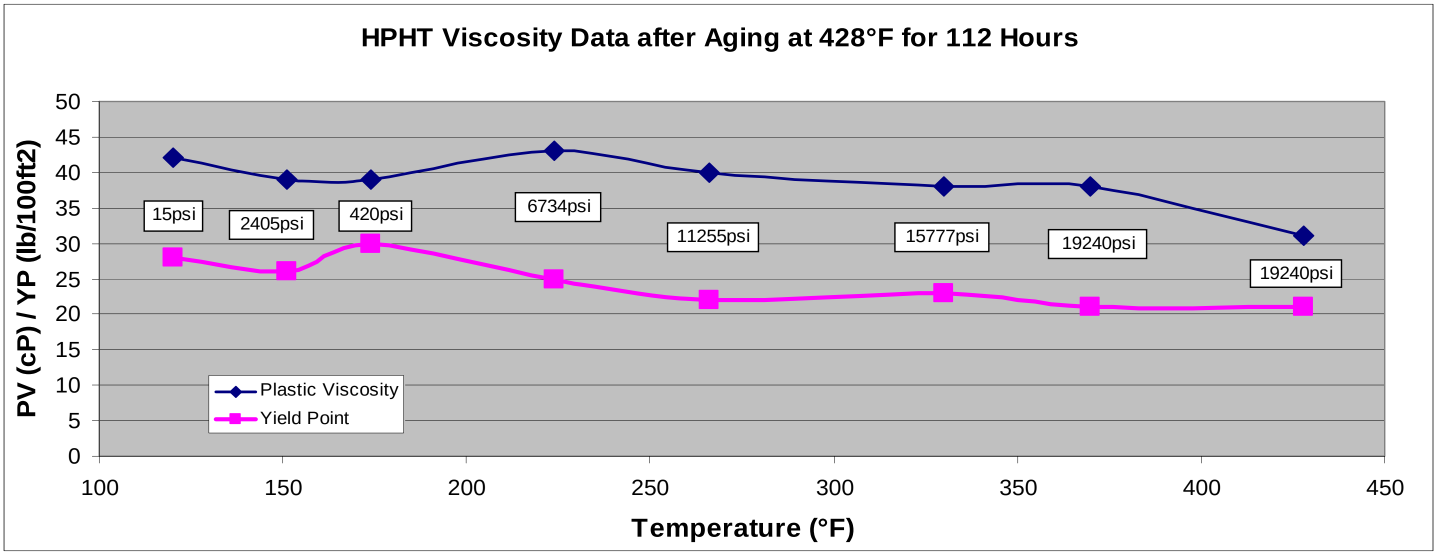

Figure 6: HPHT viscosity data for mud formulation shown in Table 3 after aging at 428°F for 112 hours

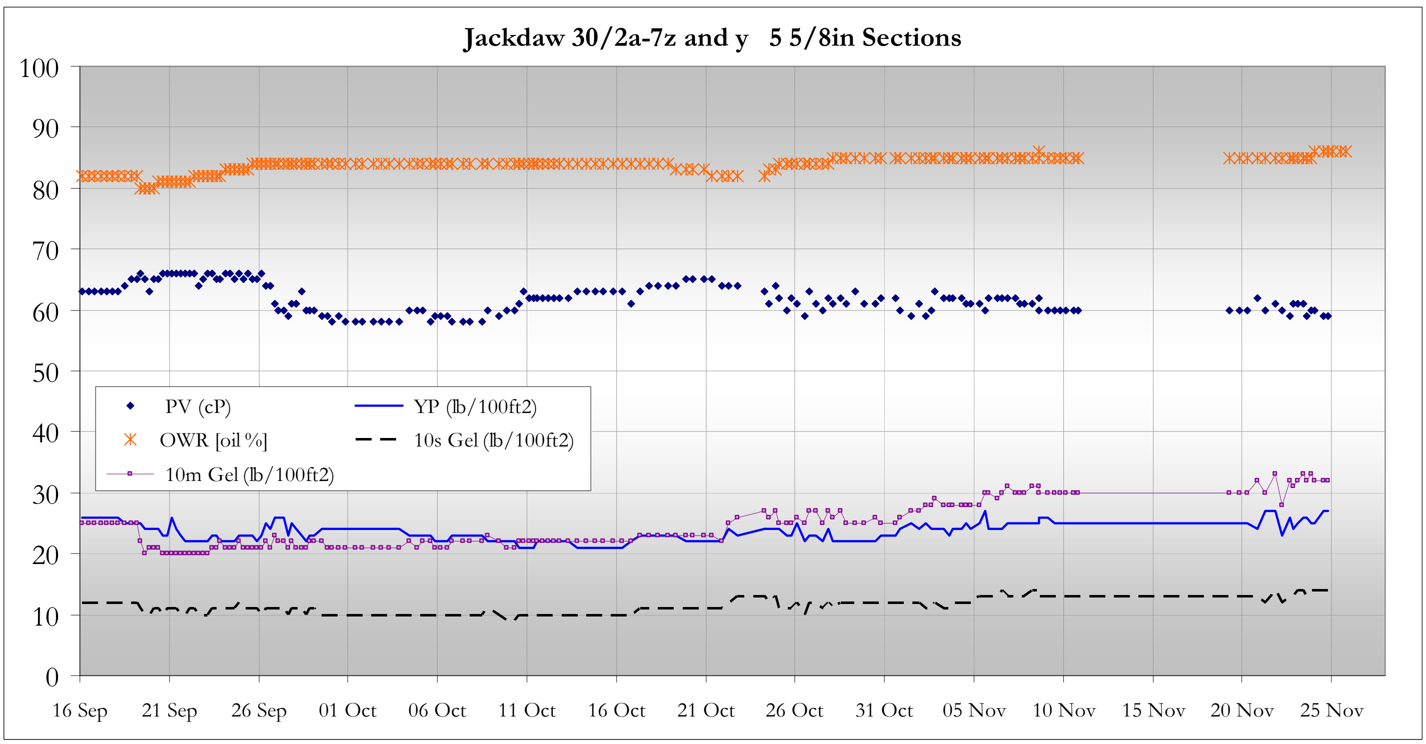

Figure 7: Mud properties as a function of time during sidetrack drilling

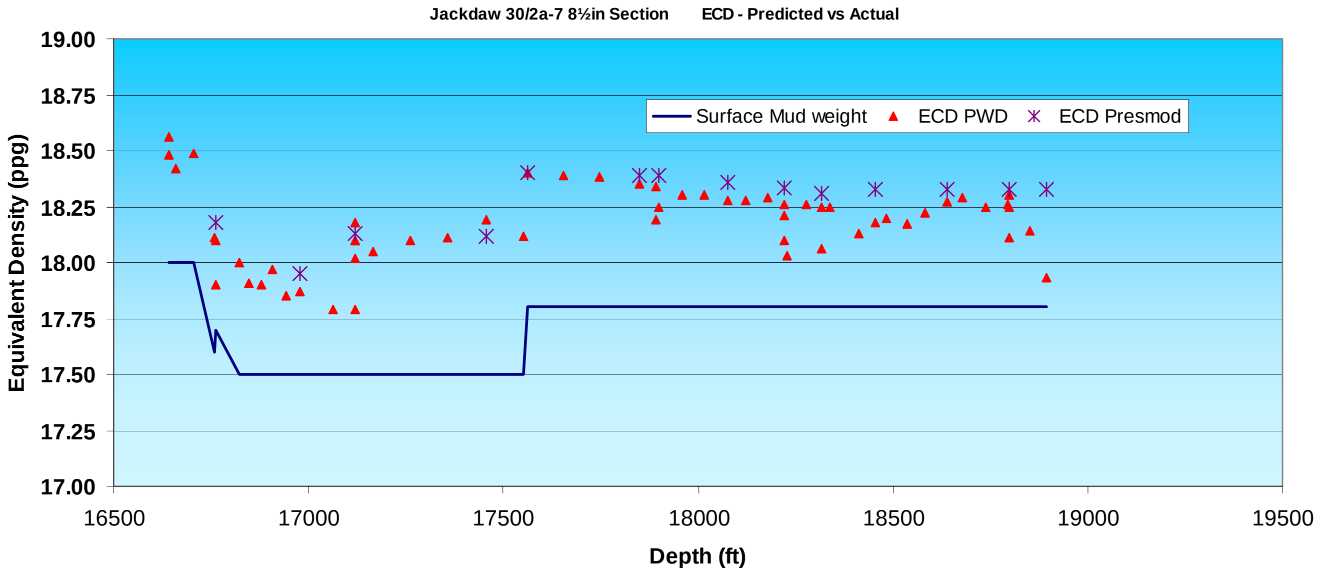

Figure 8: Comparison of measured and calculated ECD values