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New Developments in Ester-based Mud Technology

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Abstract
Ester-based mud systems have been utilized for some time to drill challenging extended reach wells from the Goodwyn and North Rankin platforms on Australia's North West Shelf. Ester-based systems are the "systems of choice" for these projects based on their combination of environmental acceptability and technical performance. In order to raise environmental standards still further, Woodside made the decision to utilize ester-based muds on mobile rigs in Australia for those wells that required an invert-emulsion mud system. Whilst a first generation ester-based mud system used on Goodwyn and Rankin platforms was considered to be the best available technology at that time, use on mobile rigs would present a much wider and more rigorous range of environments, both down hole and on surface. In order to meet these challenges it was desirable to have an ester-based mud system with improved all-round performance. Principal areas for focus being rheology and resultant ECD's, tolerance to temperature and common contaminants (particularly cement) and the lowest possible skin damage. Reductions in ECD were particularly desirable as they would also prove beneficial in extending the limits of future extended reach drilling.

This paper describes the development of the next generation ester-based NEXES mud system, referred to as NGE in this paper, and the successful field applications on one vertical exploration well and two horizontal production wells. The NGE system provided improved technical performance in all the required areas whilst maintaining environmental acceptability and providing improved rigsite handling.

Introduction
A new ester, which exhibits the lowest kinematic viscosity of commercially available esters, was identified and selected for use. New techniques were used as part of the development program. Linear viscoelastic rheology and surfactant droplet size were used to establish critical performance criteria for key aspects of the system design. Use of a viscoelastic model for drilling fluid characterization has been introduced by Baker Hughes INTEQ (BHI). It permits the examination of solids suspension characteristics of additives, which impart superior solids suspension characteristics to the fluid and may be used to evaluate rheological products in the system. Surfactant droplet size analysis is a non-conventional technique for the evaluation of emulsifiers which produce the most stable invert emulsions.

Drilling Fluids
Invert-emulsion muds have evolved over the past several decades, primarily in response to government-imposed restrictions on the discharge of contaminated cuttings.

Ester-based muds (EBM) were introduced in the early 1990's. EBM falls into a broad classification of invert-emulsion muds known as synthetic-based muds (SBM), and are classified according to their molecular structure. Early SBM's were made from ester, acetal, ether or polyalphaolefin (PAO) base fluids, followed by internal olefins (IO), linear alpha olefins (LAO) or normal paraffins.

Development Process
A project was undertaken to develop a new brine-in-ester emulsion drilling fluid based on NX-3500, an experimental ester. This system would be recognized as a new "standard" in terms of environmental acceptability combined with technical performance. The need to develop an improved ester system existed because of pending changes in environmental regulations governing the use of synthetic drilling fluids in the North Sea. At the time of development the direction indicated by UK regulatory authorities was to ban the discharge of non ester based syntethic based muds by January 1, 2001. Norway allowed only ester-based fluids for exploration in its offshore waters.
Development of a drilling fluid system with the NX-3500 ester involved evaluation of all additives required to formulate a drilling fluid that has acceptable properties and is stable to 300°F (149°C). Testing included the evaluation of emulsifiers, viscosifiers, rheological

modifiers, wetting agents, and fluid loss additives.
a) **emulsifier evaluation** based upon droplet size measurement techniques; b) **organophilic clay evaluation** utilizing the new technology of linear viscoelastic measurements accompanied by conventional rheological measurements; and c) **rheological modifier evaluation**, again using linear viscoelastic and conventional rheological measurements; d) **filtration control agent testing** by HTHP filtration; e) **wetting agent evaluation** using both conventional and linear viscoelastic rheological evaluations.
Additional work was performed to evaluate lubricity characteristics, elastomer compatability, formation damage, solids tolerance, and suspension characteristics of the system. A series of formulations were evaluated to compare the properties of the NGE system to its predessor, the BIO-GREEN fish oil ester system, referred to as the FOE system.

Ester Selection
NX-3500, the base ester of the NGE system, exhibits the lowest kinematic viscosity when compared to all other esters that are currently commercially available. The ester employed in this system exhibits superior hydrolytic stability compared to that of the FOE ester. Several esters were evaluated with consideration to environmental compliance, kinematic viscosity, elastomer compatibility, lubricity, alkaline and temperature stability.

Environmental Compliance
Environmental test results reveals this new system meets current environmental requirements for use in Australia and the Gulf of Mexico. Australian regulatory authorities viewed EBM as a step change improvement on previous syntethic systems. In light of the Australian regulatory authority's preference towards EBM, and Woodside's environmental policy, the decision was made to introduce the new EBM in this market area.

Kinematic Viscosity
In addition to exhibiting the lowest kinematic viscosity of all other esters that are currently commercially available, the ester employed in this system exhibits superior hydrolytic stability compared with that of FOE. Typical physical properties of NX-3500 and FOE are described in Table 1. Both products exhibit similar characteristics except for the kinematic viscosity for FOE which is almost 30% higher than that of NX-3500. Kinematic viscosity is an important physical property of base fluids because of its effect on the rheological properties and hydraulics. Fluids with a high kinematic viscosity generally exhibit high plastic viscosity, annular pressure losses and equivalent circulating densities (ECD's). Kinematic viscosity also has an effect on the volume of ester needed to prepare an EBM system. Brine droplets

This development program was divided into five phases: emulsified into the ester increase plastic viscosity and a balance between volumes of ester and brine must be established. By using an ester with a low kinematic viscosity, higher volumes of brine can be used in formulating a finished barrel of mud. The net effect of this is to reduce mud costs and the environmental impact (from discharges), by reducing the volume of ester in an EBM.

Elastomer Compatibility
Another important performance measure is the compatibility of the ester with oilfield elastomers. Incompatibility between the ester and elastomer can result in changes to the volume and hardness of the elastomer, and subsequent field failures. Figure 1 shows the results of elastomer testing in accordance with ASTM D471 and DIN 53521 protocols. These standards describe the requirements for the exposure to fluids and procedures to determine volume changes.
Test results for synthetic fluids as well as other esters are shown for comparison. Test results indicate that NX-3500 is slightly more aggressive than other base oils.

Lubricity
Fluid lubricity has become more important as well geometries have become more complicated. The implementation of drilling motors and stearable drilling assemblies require that the drill string slide during orientation. The linear friction tester (LFT) can measure the static coefficient of friction as well as the sliding (dynamic) coefficient of friction for drilling fluids. Lubricity tests were performed on various muds to determine their comparative performance with the LFT and the lubrisometer, a rotary friction test device. The ester systems being evaluated - FOE system, VOE system, and NGE were compared with a high performance water-based field mud (AQUA-DRILL™), the field mud treated with a lubricant, and two synthetic fluids. Formulations for NGE and FOE systems were the same as those used for the consistometer evaluation. The other muds were 12 to 14 lb/gal formulations. The results of these tests are described in Table 2. NGE produced one of the two lowest coefficient of friction values as measured on the lubrisometer. Therefore, it can be stated that lubricity characteristics of NGE fluids compare favorably to all the other systems tested.

Ester Hydrolysis
Esters will undergo hydrolysis when exposed to elevated temperatures. An examination of this condition revealed a significant difference in rate of breakdown between NX-3500 and FOE. Emulsions were prepared and hot rolled for 16 hours at 250°F (121°C) and higher temperatures. Following the aging period, the samples were analyzed on a gas chromatograph mass

spectrometer (GCMS). The products of hydrolysis were then plotted vs. aging temperature. As aging temperature increases, hydrolysis increases and is more pronounced for FOE. Another test was conducted by adding lime in increasing concentrations to the emulsions which were dynamically aged for 16 hours at 250°F (121°C) Test results indicate that ester hydrolysis increases as lime treatments are increased. Again, hydrolysis was more pronounced for FOE.

Emulsifier Selection

Emulsifier selection was based on the average droplet size of the invert emulsion ($CaCl_2$ brine in NX-3500). Droplet size determinations were made initially and after heat aging for 16 hours at 300 °F (149°C).
The average droplet size of the invert emulsion was measured using a light-scattering technique with a Malvern Instruments Mastersizer µ+ Version 2.15 with a QS small volume dispersion unit. The emulsion samples were dispersed in toluene following the procedure in the Malvern manual. Data analyses were based on the volume mean (average) droplet size. This average droplet size is calculated by multiplying each particle diameter by the volume of material in all particles of that size and summing. This value is then divided by the total volume of all particles.
Brine-in-oil emulsions were prepared and evaluated using surfactants, and blends of surfactants, with various hydrophilic/lipophilic (HLB) index values. HLB is related to the size and strength of the hydrophilic (polar) and the lipophilic (non-polar) groups of the surfactant molecule.
The distribution of particle sizes was measured using a Malvern Mastersizer. Droplet size determinations were made initially and after heat aging 16 hours at 121 °C (250 °F). The analyses of results were based on the (D[0,5]) and the (D[0,9]) droplet size.
Weighting materials were not used during the screening process because of particle size overlap with the brine droplets. All the surfactants evaluated formed a stable emulsion in the NX 3500. The criteria used to evaluate emulsifiers were:

- Average droplet size of the unweighted emulsion < 10 microns, initially and after heat aging.
- Difference between initial and heat aged average droplet size ± 4 microns
- HPHT filtration control was used to differentiate from criteria “2” above

Organophilic Clay

Several organophilic clay types and chemistries were evaluated using dynamic oscillatory and traditional oilfield rheological test methodology.

Rheological Modifier

Dynamic oscillatory and conventional rheological testing methodologies were also used for screening rheological modifiers. The tests were designed to evaluate the degree to which each additive modified the structure formed by the organophilic clay network. These were balanced against the contribution to viscosity, particularly plastic viscosity, measured with each additive.

Dynamic Oscillatory Tests

Dynamic oscillatory tests provide information about the efficiency of structured fluids that are not apparent in traditional rheological tests. In these tests the strain response to a sinusoidially varying stress is separated into in-phase and out-of-phase components.
Viscoelastic materials exhibit a two component response because some of the energy applied is stored elastically and some is lost. Viscoelastic components are quantified G' and G", and used as sensitive probes of gel structures. The term “storage modulus” is used to describe G' since elastic energy is stored, whereas “ loss modulus” is used to describe G" since viscous energy is lost. G" is related to the “liquid-like” characteristics of the material, e.g. the flow behavior of a drilling mud. G ' is related to “solid-like” behavior, e.g. how well a drilling mud will suspend solids.
Viscoelastic behavior can be sub-divided into linear and non-linear responses. The most common way of quantifying linear viscoelasticity is through dynamic oscillatory tests. Linear viscoelastic properties are observed when shear stress and strain are proportional. Small deformations are applied to the sample and the viscous and elastic responses are measured. The gel strengths of drilling muds are best measured using small deformations, i.e., through linear viscoelastic tests. Non-linear viscoelasticity implies that shear stress and strain are disproportionate. Large deformations are applied to the sample in non-linear viscoelastic tests. These tests measure the flow behavior of drilling muds, i.e. shear viscosity and shear thinning behavior.

Optimized EBM System

In the laboratory development of the new EBM system several classes of organophilic clays, surfactants and rheological modifiers were evaluated, individually and in combination with one another, Advanced and insightful techniques, such as droplet size measurements and dynamic oscillatory rheological testing were utilized to develop the optimized formulation.
Product concentration studies were carried out for individual, and combinations of products.

Performance Tests

The Ester Water Ratio (EWR) formulation was subjected to performance tests detailed below.

Static Barite Sag

A static sag test was conducted at 290°F (143°C) and 10,000 psi for 48 hours using a consistometer (Figure x. The test was conducted without the oscillating bob. The mud formulations and properties used in this test are given in Table 3.. Test specifications for maximum free oil and density differentials were established. Both the NGE and FOE systems exhibited satisfactory results.

Return Permeability

A formation damage study was conducted by performing return permeability work on a Berea sandstone core. The test parameters and results obtained were as follows:
500 psi overbalance for 2.5 hours
150°F (66°C) Test Temperature
Breakout Pressure - 5 psi
Return Permeability control - 100%
Return Permeability with Fluid Loss Additive - 100%

HPHT Rheology

Routine rheological tests do not consider the influence of downhole temperatures and pressures on the rheological behavior of the EBM. This is particularly important in ERD wells where hydraulics performance is critical for hole cleaning, ECD, bit and BHA hydraulics. The Fann® Model 70 viscometer was used to determine the effects of temperature and pressure on the rheological properties of an olefin and the new EBM systems. The benefits of the optimization work done in the laboratory development of the EBM are apparent from this testing.

Field Applications

Maia-1

The FIRST well to be drilled using BAKER HUGHES *INTEQ*'s NGE ester based invert emulsion drilling fluid was MAIA-1, situated on the North West Shelf of Australia and drilled with the Ocean General MODU.

The FOE SYSTEM ester based mud used to drill Goodwyn-14,15,16,17,18,19 Perseus-02 and 03 wells on Woodside wells on the North West Shelf of Australia was a qualified success. Lessons were learned from this project in terms of planning, fluid formulations (most importantly ester / water ratio) and maintenance of the NGE system.

Prior to drilling Maia-1, an extensive formulation and optimisation project was undertaken by BHI Houston Fluids Technical Services Centres during 1999 to 2001. This project focused on a 1.5 s.g. formulation which would be stable to 300°F and exhibit minimal barite sag. The objective of the project was to formulate a 2nd generation ester system for use on Woodside's Goodwyn platform.

On mixing the recommended formulation at the Mud Plant the NGE fluid was, as expected, found to exhibit very low viscosity. Normally a rheology modifier is added to newly mixed drilling fluids at the mud plant to bolster low end rheology (6 rpm), however it was decided that as the fluid would be transported unweighted this addition would be unnecessary.

The 1255 m of 12¼" section was drilled successfully to a depth of 3179 m. Maia-1 was a vertical exploration well, the 12 ¼" section was drilled from the base of the Mandu formation to the Angel sand in 69 hours. On completion of the section the condition of the hole was found to be excellent.

Open hole logging was carried out without incident and the well was then plugged and abandoned. The mud was displaced from the hole and used on the Echo Yodel Development.

The NGE system was judged to have met and exceeded all the operators expectations.

There were no health issues raised while drilling with NGE and reports from the drill crews and mud engineers were favourable is as much as cleaning and HS&E issues were better than with other inverts.

At the end of the 12¼" section the NGE drilling fluid was backloaded for use on the upcoming Echo/Yodel project.

Echo Yodel

The Echo Yodel project involveed the development of the Echo Yodel Lower E reservoir via two satellite wells tied back directly to the GWA platform via a 12" 23km production line. Initial rates were expected to be approximately 30,000 Bbl/d condensate and 300 Mmscf/d of gas.

The Echo/Yodel field lies 21km southwest of the Goodwyn A platform. It was discovered in 1988 by Echo-1, which penetrated a 19m gross hydrocarbon column in fluvio-deltaic sandstones of the Triassic Mungaroo Formation. The northwesterly dipping reservoir units are truncated by the regional unconformity MU, which also dips to the northwest. Overlying Cretaceous shales provide the seal to the accumulation.

Yodel 3

Yodel 3 was the first of two development wells in the Echo/Yodel gas-condensate field on the North West

Shelf to be drilled with the new EBM. EBM was used in the 12¼" and 8½" sections. The 12 ¼" section was drilled with the NGE mud backloaded from the Maia-1 well which was contaminated with seawater and reduced the ester/water ratio from 80/20 to 70/30. Weather limitations during Yodel 3 did not allow any base ester to be taken on to the rig and the 12 ¼" section was drilled with no base ester treatment. Hydraulics were critical due to the design of the well as the rig pumps did not have a high enough capacity for Powerdrive Rotary Steerable Tool (RST) at >2800m depths. The Powerdrive RST requires minimum of 600psi pressure drop across the bit and 800gpm. This is a very tight envelope to achieve with the rig mud pumps and 5-1/2" liners. The rig's 5" DP had 2.75" tool joints which did not aid the hydraulics limitations. Very high EBM mud rheology was also a contributing factor, base oil or thinners were not available to reduce rheology. In future, installation of 5" pump liners may be a solution, max flow rate would be limited to ~850gpm. Due to the high rheology of the mud, high surface pressures were experienced, however the section was drilled to TD, at a reduced flow rate to combat the high surface pressures. It is worth noting here that if the same level of contamination occurred using a base ester with a higher kinematic viscosity, it may not have been possible to drill to section TD, as the resulting rheology would have been even higher than experienced on Yodel 3. Inclination was built from 0 to 81 degrees in the 12¼" section and then built to horizontal in the 8½" section. By their chemistry, ester muds are susceptible to cement contamination, resulting in hydrolysis of the ester. The NGE base ester proved to be resilient to moderate cement contamination, which supports the lab data. Whilst reverse circulating out the cement/spacers after cementing the $9^5/_8$" liner and drilling out cement/shoe/rat hole for the 8½" section, there was no indication that the cement had caused any detrimental impact on the mud properties or performance. After drilling out the $9^5/_8$" shoe a large reduction in mud weight, from 1.4sg to 1.2sg, was required. This was achieved by the addition of base ester that also treated the ester/water ratio back to the programmed 80/20 which in turn brought the rheology back to the required specification. The 8½" section was drilled with no mud related problems. Problems were encountered during the running of the ESS; it is believed hole geometry caused this. Prior to running the screens the mud was cleaned-up by passing over 250 mesh shaker screens to reduce the risk of plugging the screens with mud solids. Once the screens were expanded the well was displaced to brine and no downhole losses were evident, indicating that the filtercake formed was in excellent condition. Prior to running the completion an isolation plug was run and the well was cleaned-up using a combination of chemical pills. The well cleaned-up to the required specification (<80NTU) after 18,000 strokes. It should be noted bottoms-up for the first pill pumped was 13,000 strokes.

Yodel 4

Yodel 4 was the second of the two development wells to be drilled with the EBM. EBM was again used to drill the 12¼" and 8½" sections. 600 bbls of the mud backloaded from Yodel 3 was used as seed mud to prepare and extra 400 bbls of EBM. This was performed at the mud plant and was the only reconditioning that was required. The 12 ¼" section was drilled with no difficulties and the mud properties were easily maintained. Inclination was built from 0 to 81 degrees in the 12 ¼" section then built to horizontal in the 8 ½" section. Again, the NGE system proved to be resilient to moderate cement contamination. When reverse circulating out the cement/spacers after cementing the $9^5/_8$" liner, and drilling out cement/shoe/rat hole for the 8½" section, there was no indication that the cement had caused any detrimental impact on the mud properties or performance. After drilling out the shoe, a large reduction in mud weight, from 1.4sg to 1.2sg, was required. This was achieved by the addition of unweighted EBM (0.93sg) and by centrifugation. Ten hours critical path time was planned for the operation but only four hours was required. The 8½" section was drilled with no mud-related problems. Geological uncertanties and wellbore stability problems were encountered whilst drilling the 8½" section. The primary target came in deeper than expected and the secondary target was not penetrated. Well TD was extended in an attempt to locate the secondary target, but wellbore stability problems were encountered so TD was called before the second target was penetrated. Prior to running the screens the mud was cleaned-up by passing over 250 mesh shaker screens to reduce the risk of plugging the screens with mud solids. Once the screens were expanded the well was displaced to brine. Downhole losses of 2 bbl/hr were evident, indicating that the filtercake formed was in good condition. Prior to running the completion, an isolation plug was run and the well was cleaned-up using a combination of chemical pills. The well cleaned-up to the required specification of <80NTU 2,000 strokes after the last pill arrived at surface.

Conclusions

1. A new EBM system was "invented-on-schedule" for field testing in the 12¼" interval of Maia-1. The development process was facilitated by effective communication and coordination of efforts between the global development teams.
2. The system is simple, with robust filtration and rheological control generally achieved with only 3 additives.
3. The EBM system remained stable throughout the

project and did not require to be reconditioned at the mud plant throught the duration of the 3 wells drilled. Reconditioning from well to well was mimimal and easily accomplished at the rig site.

4. Measured and calculated ECD's for the 1.2 and 1.4sg mud was very low, typically 0.01 to 0.03sg higher than the active mud weight. Measured ECD was achived by use of a PWD sub.
5. The new system was instrumental in successfully drilling the 12¼" and 8½" hole sections of the Echo Yodel Development program.
6. Large changes in mud weight from 1.2 to 1.4sg during the 12 ¼" sections then back to 1.2sg during the 8 ½" sections were achevied without difficulty and without any detrimental effects to the mud properties.
7. Figures 2 and 3 show that drilling perfomance was very close to technical limit, in some instances the technical limit was exceeded.

Figure 1 . Elastomer F-HNBR Test Results after 72 hrs

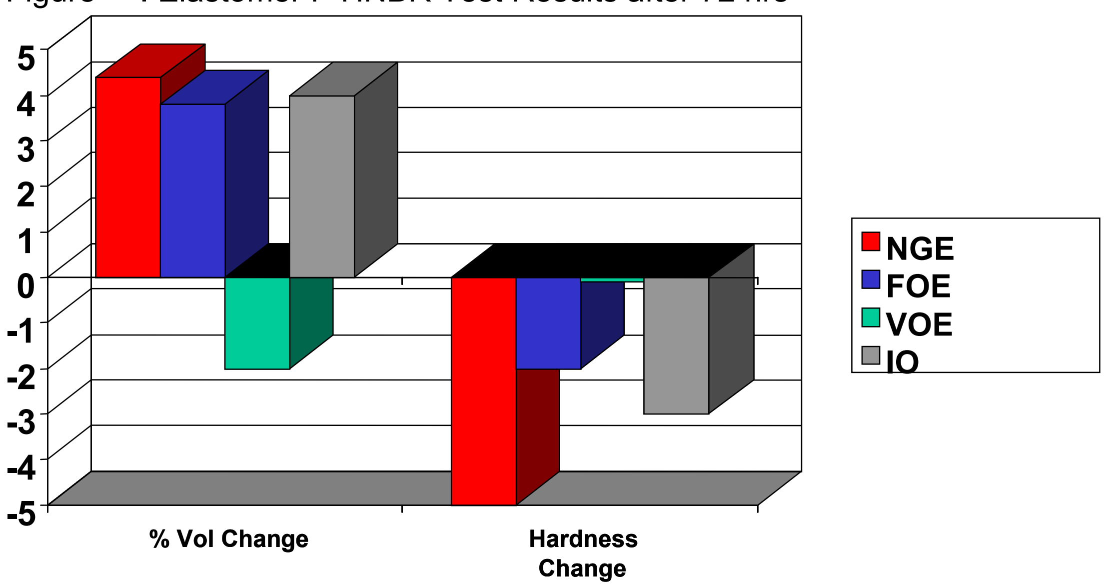

Table 1 . Typical Physical Properties of Esters

Physical	NX-4200	FOE
Specific Gravity	0.858	0.85
Kinematic Viscosity, cSt @°C	4.25	5.5
Kinematic Viscosity, cSt @ °C	1.56	-
Pour Point, °C	-29	-
Flash Point (PM), °F	313	>302
Highest Temperature Stability (HTSL),°F	300	300

Table 2. Lubricity Test Results from Various Esters, Synthetics, and Treated Water Base

Test	LFT (Sliding)	Lubrisometer (Rotary)
AQUA-DRILL Field Mud	-	0.28
AQUA-DRILL + 3% EBL	-	0.17
HDF 2000 mineral oil	-	0.20
SYN-TEQ 16/18 IO system	-	0.19
FOE system	-	0.16
VOE system	-	0.15
NGE system	0.27	0.15

Table 3. Formulations and Properties for Muds Subjected to Static Barite Sag Testing

Product	NGE system	FOE system	Test Specifications
EWR	85/15	80/20	
Mud Weight,	12.5	12.5	
Organophilic Clay,	5 CARBO-GEL®	4 DFE-434	
OMNI-MUL™, lb/bbl	9.7	13.1	
DFE-433, lb/bbl	1.5	2.0	
MIL-GEL®, lb/bbl	-	35	
STATIC CONSISTOMETER TEST RESULTS			
Free Oil, ml	13	0	< 50 ml
Density Differential,	0.0	0.2	< 2 lb/gal

Figure 2
Time breakdown of Yodel 3 drilling performance

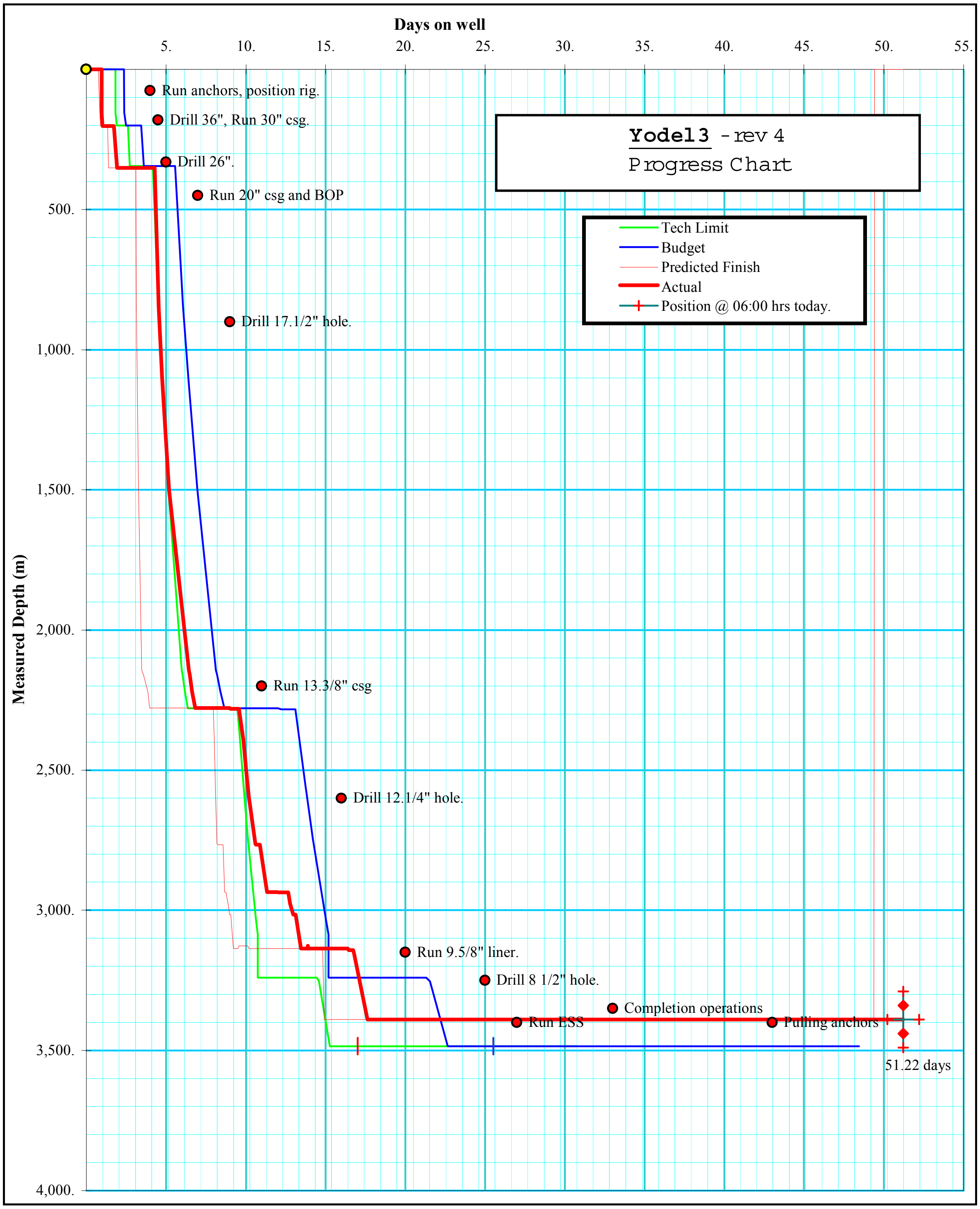

Figure 3.
Time breakdown of Yodel 4 drilling performance