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Using Real-Time Hydraulics Modeling to Complement Annular-Pressure-While-Drilling Data

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Abstract

Accurate, real-time downhole hydraulics data are critical to successfully drill challenging wells. In many situations, operators rely on annular-pressure-while-drilling (APWD) tools to provide downhole information based on actual wellbore conditions, thereby enabling wellsite personnel to implement corrective actions in the event of impending problems. These measurements need to be supported by a real-time hydraulics system that can provide the "what-should-be" scenario to complement the "what-is" scenario provided by the APWD tool and give an early indication of an unscheduled drilling event. A system that calculates downhole hydraulics based on surface parameters has been used in key operations around the world to reduce hydraulics-related problems. The real-time hydraulics system has also substituted for the APWD after the tool failed, or when no real-time data were available, such as during trips or running casing.

This paper reviews several case histories where this technology was successfully applied to avoid, identify, and respond to problems that could have, or did, develop during well construction. During normal drilling conditions, the calculated equivalent circulating density (ECD) typically has been within 0.1 lb/gal of APWD values. In many cases, drilling problems were preceded by noticeable differences between measured and calculated ECDs. Step improvements have been made to detect in advance some of these problems, such as poor hole cleaning, wellbore instability, bit balling, and lost circulation. Lessons learned and areas of improvements to adapt the system to various drilling conditions have been identified and addressed in the paper.

Introduction

The causes and consequences of hydraulics-related problems are well known and documented.[1] Poor wellbore management can result in a variety of problems such as borehole stability, lost circulation, well-control problems, etc. In general, the most critical problems are associated with narrow operating windows caused by the convergence of formation and fracture pressures. The introduction of annular-pressure-while-drilling (APWD) tools, arguably one of the most significant developments for monitoring drilling performance,[2] has greatly simplified early detection of problems. By providing an instantaneous measurement of actual downhole pressures, APWD has gained wide acceptance as the tool of choice to guide drilling operations in difficult and/or uncertain situations.

The numerous benefits of APWD to monitor drilling problems have been reported.[3-7] Careful analysis of APWD trends can be used to predict impending problems. However, these trends need to be analyzed in the context of other drilling parameters and the resulting data overload may make timely intervention difficult at best. The situation can be exacerbated by the lack of suitable reference points to compare the expected conditions to measured-APWD values. This may make it difficult to determine if current drilling conditions are acceptable, and what adjustments are needed to correct potentially difficult situations.

One of the key advantages of accurate real-time ECD modeling at the wellsite is that it provides a "what-should-be" scenario to compare with the "what-is" scenario provided by the APWD, as well as other downhole and surface parameters. By comparing the expected values to the measured parameters, wellsite engineers may be significantly better prepared to determine the cause of any deviation from expected behavior and whether corrective action is required to the current drilling conditions. No practical models exist that can reliably predict various hydraulics-related problems such as kicks, wellbore washouts, bottomhole assembly (BHA) balling, shallow water flows, etc.

Under normal drilling conditions, a correctly designed wellsite hydraulics software package should closely match trends from real-time APWD data. However, in the event of downhole problems, APWD data that represent actual conditions in the annulus can detect the problem, via an unexpected deviation in the measured data trend. This deviation relative to the model data, combined with existing and recent drilling parameters, should provide early indications to wellsite personnel on the most likely cause of any unplanned or unsafe wellbore conditions and allow timely corrective

actions. It is important to note that APWD data alone often only indicates the existence of, but not the type of problem. APWD data still need to be analyzed along with other measured parameters to correctly diagnose the problems.

One significant technology gap that still exists in the wellbore construction process is the inability to monitor, in real-time, downhole pressures during drillstring trips and casing/liner runs. Current APWD technology relies on mud pulse telemetry, whereby the information measured by the downhole tool is pumped to the surface as a pressure pulse when the drilling fluid is being circulated. When the mud is not being circulated during trips or when making connections, it is not possible to transmit any measured data to the surface. This is a critical issue, especially for deepwater drilling operations, where the margin between fracture gradient and pore pressure is small enough to place very strict limitations on operational parameters. Today, one of the major sources of whole-mud losses downhole occurs during casing runs and cementing operations, and minimizing these losses would deliver significant cost savings to the operator.[7]

The advent of high-speed desktop computers has facilitated the development of programs that can process complex and voluminous data. When correctly designed, real-time hydraulics models can deliver valuable output at the rigsite, where it is most needed, within a time frame that allows timely responses to be implemented.

The aim of this paper is to review incidences from actual drilling operations where real-time hydraulics software, in conjunction with APWD data, was used to identify and respond to recognized problems. In many cases, this approach was used to prevent major problems on the well and greatly reduce non-productive time, and ultimately led to significant cost savings for the operator of the well.

Real-Time Hydraulics Modeling

The real-time hydraulics system (RTHS) discussed in this paper runs on a desktop computer linked directly to the rig data-acquisition system. In most cases, a universal data transfer protocol such as WITS is used; however, in some cases, proprietary protocols unique to the data provider have also been used. The RTHS accepts conventional surface measurements associated with the drilling process, together with certain manual input parameters not measured by sensors. If this link is bi-directional, RTHS-calculated hydraulics data can be sent to various locations on the rig for display. Downhole annular-pressure data from the APWD tool are not required as input, but are typically displayed on the output screen alongside the modeled ECD. The preferred data transmission speed for the input parameters is 1 Hz or faster, primarily for tripping operations.

The RTHS relies heavily on transient temperature simulations to predict downhole temperature profiles. The temperature simulations utilize suction and flowline temperatures to calculate downhole profiles under circulating and static conditions. The RTHS is structured to utilize measured downhole temperatures, such as those provided by the APWD, to dynamically modify calculated temperature profiles to match the measured data.

Temperature and pressure effects on density and rheology are key to accurate downhole hydraulics calculations. The RTHS uses calculated downhole temperature profiles to continuously adjust drilling fluid properties. The density models are primarily based on PVT (pressure-volume-temperature) characteristics of the liquid phases of the drilling fluid. Downhole rheology of the drilling fluid is calculated by 3-D interpolation among pressure, temperature, and shear rate based on rheology measurements at the wellsite and HTHP/LTHP measurements on viscometers. The RTHS also includes a sophisticated transient surge-and-swab pressure model that includes temperature and pressure effects on the density and rheology of fluids, and is adapted for use in a real-time mode. In addition, transient cuttings distribution in the annulus can be modeled, allowing rapid identification of regions in the wellbore where cuttings may accumulate. A more detailed discussion of the operation of the RTHS is given by Zamora, *et. al.*[2]

Case Histories

Table 1 summarizes three exploratory wells discussed in this paper where the RTHS has been successfully used in conjunction with APWD to detect drilling problems. Examples are provided that illustrate how (a) bit/BHA balling, (b) tight hole, (c) gas kick, and, (d) borehole washout affect APWD data, and how results from wellsite hydraulic simulations can be used to detect such problems. Results are also included to show how the RTHS was successfully used as a guide to run a liner in a deepwater well without major problems. Relevant mud and other properties are shown in **Table 2**.

The following observations apply to all the cases being presented:

- In general, calculated ECDs during normal drilling operations were within 0.1 lb/gal of APWD measurements when available.
- PWD data shown in the figures are unprocessed, unless otherwise noted.
- Calculated RTHS ECD is shown at the APWD tool location when both are shown on the same graph. In other cases, ECD at the last casing shoe is displayed.

Bottomhole Assembly Balling

In this particular example from Well A, an operator

was drilling a deepwater exploration well with a water-based mud system. A 10⅝-in. pilot hole was being drilled, with 8¼-in. drill collars on 6⅝-in. drillpipe. The tight annular clearance implies that any restrictions across the BHA could have a significant impact on the ECD. The ECD log, as a function of time for the APWD measured and RTHS calculated values, is shown in **Fig. 1**. As shown during the first 3 hours on the graph, both calculated and measured ECDs were in the range of 13.7 – 13.8 lb/gal at a flow rate of 740 gal/min. After drilling 350 ft, the measured ECD gradually increased to 14.3 lb/gal for the same flow rate, while the model data continued to track 13.7 lb/gal. At this point, the reason for the discrepancy between the APWD and model data was believed to be related to balling. A decision was made to circulate a sweep in an attempt to clean the BHA. The sweep consisted of coarse and abrasive lost-circulation material, together with an anti-balling agent, in a low-viscosity pill. The sweep produced immediate results, reducing the measured ECD down to 13.7 lb/gal while all other drilling conditions were maintained constant. Based on the correct identification of the BHA balling as the source of the high ECD and the excellent response observed after circulating the sweep, sweeps were subsequently circulated regularly until TD of the interval. With continued sweeps at regular intervals, the APWD and model ECD data maintained good agreement throughout the rest of the interval.

Tight Hole/High Rheology

Fig. 2 shows data that were generated while drilling the 8½-in. interval in Well A. During this interval, the mud weight was reduced by 0.2 lb/gal to control downhole losses. A short trip was made after drilling approximately 1,000 ft of the interval. At this point the APWD was measuring an ECD that was 0.3 lb/gal higher than the calculated ECD. During the trip, several tight spots were encountered that required additional reaming. In addition, the mud system was diluted with premix base fluid and brine to reduce the drilling fluid viscosity. PV/YP were reduced from 36/26 down to 29/18. No tight spots were encountered running back into the hole, with only the last stand needing to be washed to bottom. When back on bottom and drilling ahead, the calculated ECD did not change significantly; however, the measured-APWD ECD reduced within 0.1 lb/gal of the calculated ECD. In addition, the rate of penetration increased to 56 ft/hr, up from 37 ft/hr prior to the short trip. As drilling continued, the modeled ECD showed excellent agreement with the APWD data for the rest of the interval.

Borehole Washout

Fig. 3 shows a section of data collected while drilling the 12¼-in. section of Well B. Excellent agreement was obtained between the APWD and RTHS results during the first 7 hours. The APWD decreased by 0.12 lb/gal as

drilling continued, while the RTHS-calculated ECD remained approximately constant. At that point, it was believed that borehole washout was occurring since a sandstone formation was being drilled. Subsequent hole-caliper runs while logging confirmed that the hole was indeed washed out, resulting in a diameter larger than was used for the RTHS simulations. The RTHS assumed an in-gauge hole, and the resulting difference in trend between calculated and measured ECDs provided an indication of borehole washout. Though not performed at the time, hydraulics calculations using varying hole diameters could have been used to determine the degree of hole washout.

Kick Detection

Fig. 4, originally presented in a previous paper,[7] is included here for comparison purposes and for reference. The graph shows data generated while drilling the 14¾-in. section in Well C. The well was shut-in on a gas kick at the 9-hr time mark. Interestingly, the variance between the measured and calculated ECDs was detected at the surface well in advance of the kick.

It is important to note that both a borehole washout and a kick had similar effects on the APWD-measured ECD. In both cases, the APWD-measured ECD gradually decreased below the calculated ECD. Another problem common in deepwater drilling is shallow-water flow that could also cause a similar variance between measured and calculated ECDs. The multitude of scenarios implies that APWD and/or the RTHS ECD by themselves may not be sufficient to detect drilling problems in advance. It is necessary to combine downhole ECD information with other relevant information to correctly diagnose problems. Such information includes formation type, sudden changes in the penetration rate, pump pressure, pit volumes, rotary torque, among others. It is necessary to process all relevant information before making a determination of possible drilling problems to prevent a misdiagnosis of the problem.

Liner Run – Avoiding Losses

When running casing or a liner, there is no method available for directly measuring wellbore pressure in the openhole section. It is in situations such as this that an accurate real-time hydraulics model is highly valuable. In the following example, a 9⅝-in. liner is run through an 11¾-in. liner and into a 12¼-in. openhole interval. The previous leak-off test (LOT) for the 11¾-in. liner was 14.8 lb/gal and the mud weight (measured at surface) of the fluid in the hole was 14.2 lb/gal. The close tolerance between the 11¾-in. liner I.D. and the 9⅝-in. liner O.D., together with the narrow margin (0.6 lb/gal) between the mud weight and previous LOT meant that strict control of the running speed and acceleration was necessary in order to avoid losses.

Two variables that strongly influence the surge

pressure when running strings into the wellbore are pipe velocity and pipe acceleration. A detailed discussion of surge-and-swab calculations is given by Roy, *et. al.*[7] Having available the pipe velocity and acceleration (deceleration) data at high frequency allows the model to generate accurate data in true real-time, as the pipe is lowered into the wellbore. The sensors on the rig that monitor the position of the traveling block are typically capable of measuring these data at an acceptable rate. Delivering the data to the hydraulics model then allows predicted ECD pressures to be used to control the lowering of the casing/liner. Pre-job hydraulics models are used to prepare a plan, while the real-time data are used to control the job once it has started. Based on measured velocity and acceleration data, the ECD is calculated and alarms are activated when the ECD approaches a pre-determined value, alerting the driller to reduce the running speed or acceleration.

Fig. 5 illustrates the ECD at the interval TD and the 11¾-in. liner shoe for the 9⅝-in. liner as it was run into the well, together with measured depth. The string was run through the riser (18.5-in. ID) at speeds in excess of 600 ft/hr, with the ECD (model) peaking at 14.5 lb/gal for the 14.2 lb/gal fluid. Once the string was inside the 13⅝-in. casing (12.375-in. ID), the speed was increased to more than 1000 ft/hr. The running speed at this point resulted in the ECD inside the 13⅝-in. liner increasing to 14.8 lb/gal. As the liner approached the end of the 13⅝-in. casing (top of 11¾-in. liner), the running speed was reduced to less than 500 ft/hr, at which point the ECD was maintained at approximately 14.8 lb/gal.

Two 0.5-hr segments are extracted from **Fig. 5** and expanded to demonstrate the effect of running speed in different sections of the trip. The top graph shows an interval of faster running speed, while the bottom graph shows an interval with slower running speeds. Note the higher ECDs at the deeper depth even though a slower running speed was used.

Once the tolerance between the ECD surge pressure and formation breakdown pressure becomes tight, care must be exercised immediately after making connections. When the pipe is picked up to continue running into the hole, it is imperative that consideration be given to controlling acceleration. If the pipe velocity is increased too rapidly, the surge pressure may exceed the formation breakdown pressure.

As the new liner entered the existing 11¾-in. liner, both the pipe velocity and acceleration had to be reduced significantly. The average pipe velocity was then less than 250 ft/hr and the acceleration was less than 0.05 ft/s^2. The ECD at the base of the liner, as well as the shoe of the existing liner, were both at 14.75 lb/gal. The liner running operation was now at its most critical stage. The gap between the existing liner and the new liner was extremely tight. The ID of the 11¾-in. liner was approximately 10.8 in., with the OD of the new liner at 9⅝ in.

In this particular instance, the liner was run to bottom without inducing any losses. The model data do indicate that the ECD may have reached 15.1 lb/gal, which exceeds the 14.9-lb/gal LOT. Either these pressure spikes were erroneous data points or the instantaneous nature of these pressure spikes may have prevented the formation from being broken down.

Conclusions
1. Real-time hydraulics modeling at the wellsite can effectively complement APWD if available, or substitute for it when not available to prevent hydraulics-related problems in critical wells.
2. Single-point downhole pressure measurements from APWD tools should be augmented with surface-to-TD pressure profiles to determine wellbore conditions at any given point.
3. Careful and detailed analysis of the variance between measured APWD and calculated ECD in combination with other process metrics can provide an early indication of hydraulics-related problems.
4. The value of hydraulic simulations is greatly enhanced by timely intervention of wellsite personnel to modify a dynamic process and prevent problems.
5. Real-time hydraulics simulations provide a unique insight into wellbore conditions in the absence of downhole pressure measurements, whether due to tool failure, tool absence, or the lack of real-time communication of downhole measured data to the surface.
6. Deviation between measured and calculated downhole pressures could be an indication of potential drilling problems.
7. Accurate and timely identification of hydraulics-related hole problems is an essential factor in the successful completion of a well.

Acknowledgements

References
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7. Roy, S., Zamora, M., and Froitland, T. S.: "Surge/Swab Considerations in Deepwater Drilling," AADE Annual Technical Forum, Houston TX, March 1999.
8. Zamora, M. and Roy, S.: "Using True Real-Time Data Interpretation to Facilitate Deepwater Drilling," AADE Annual Technical Forum, Houston, TX, March 2001.

Table 1. Well identification for case histories				
Well ID	Location	Water Depth (ft)	Rig Type	Narrow Window
A	Brazil	3,161	Drillship	Yes
B	Nigeria	4,665	Drillship	Yes
C	Gulf of Mexico	6,286	Drillship	Yes

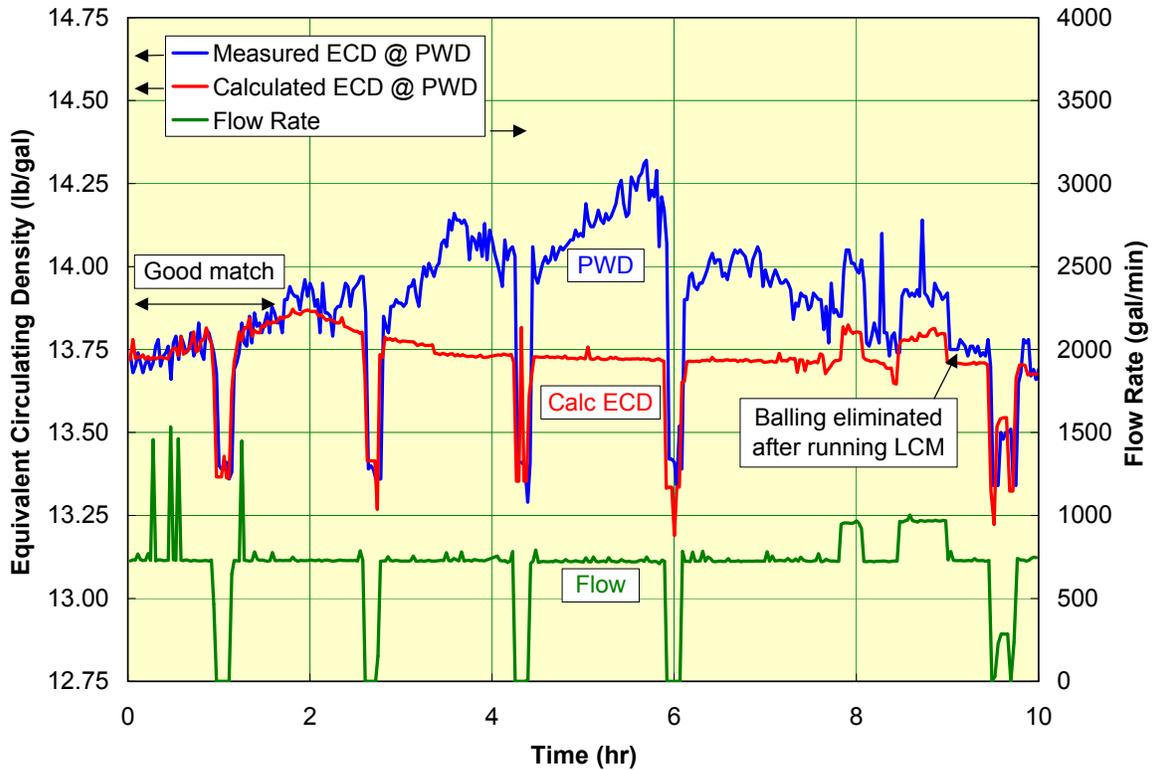| Table 2: Mud Properties for Specific Examples					
Parameter	Fig. 1	Fig. 2	Fig. 3	Fig. 4	Fig. 5
Mud Type	WBM	WBM	IO SBM	IO SBM	WBM
Well	A	A	B	C	A
Interval diameter (in.)	10⅝	8½	12¼	14¾	12¼
S/W Ratio	-/-	-/-	75/25	69/31	-/-
Density (lb/gal)	13.2	14.9	10.5	11.0	14.2
Density Temp (°F)	60	59	66	60	69
Rheology Temp (°F)	120	120	150	150	120
R600	53	98 (84)	60	57	59
R300	37	62 (53)	41	38	37
R200	31	45 (41)	32	30	30
R100	23	32(27)	21	25	21
R6	8	9 (8)	12	19	7
R3	7	7 (6)	11	17	6
10-sec Gel	7	7 (6)	19	24	7
10-min Gel	17	17 (17)	22	28	28

Fig. 1 – Well A RTHS and APWD comparison showing BHA Balling while drilling 10⅝-in. pilot hole.
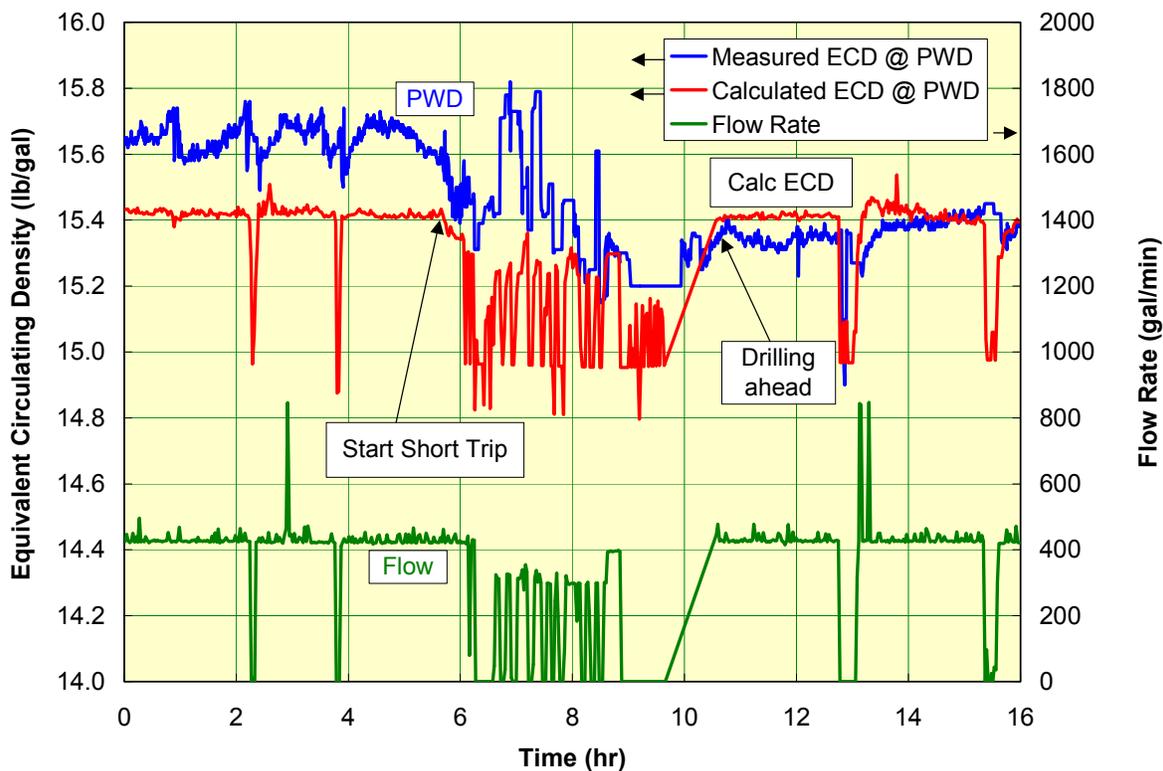

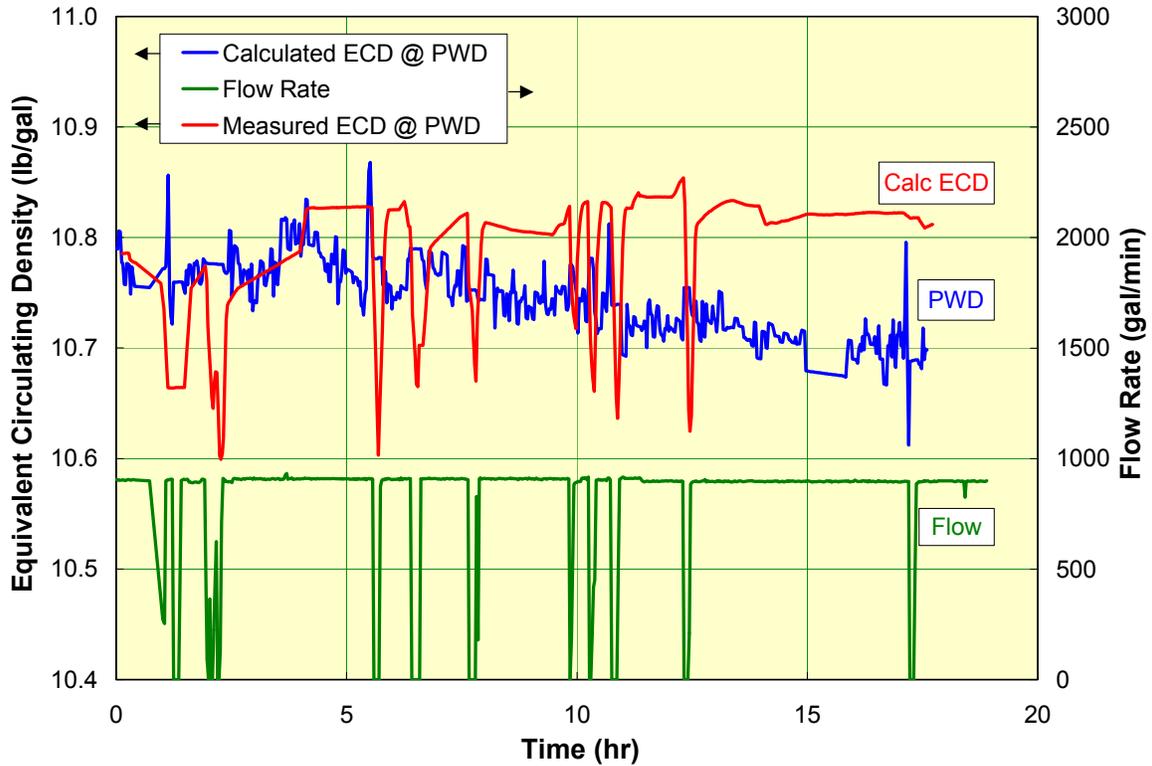**Fig. 2 – Well A RTHS and APWD comparison showing tight hole while drilling 8½-in. interval.**

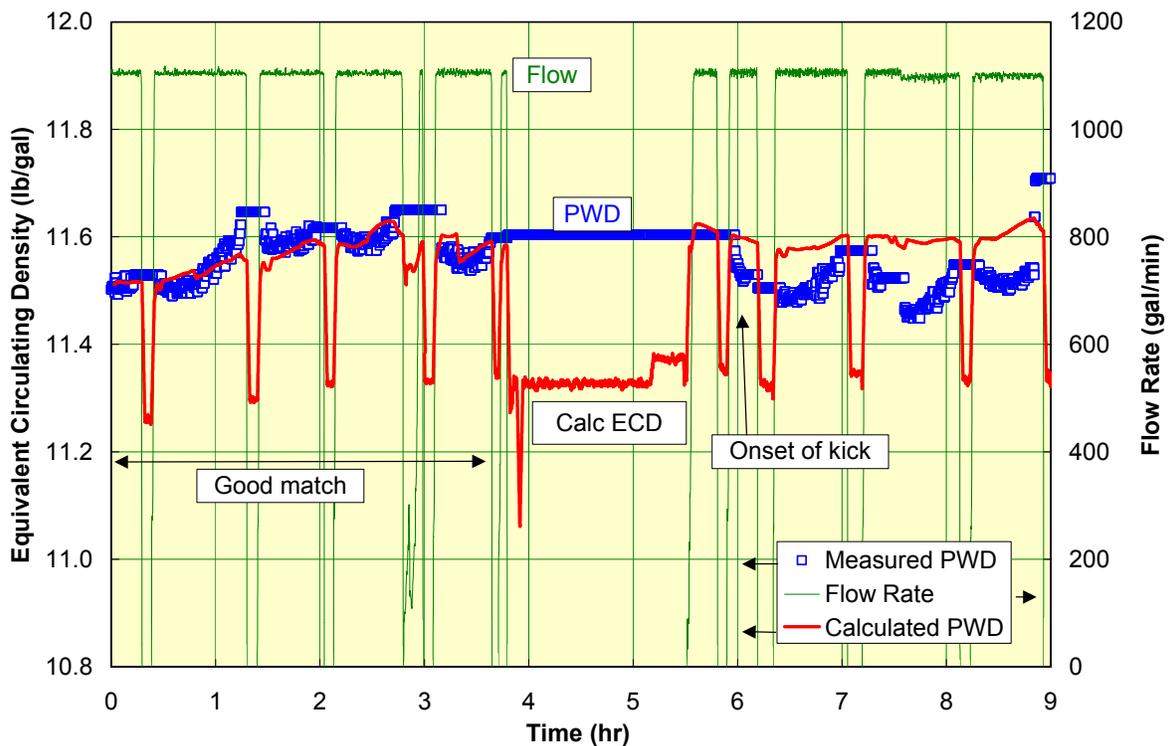**Fig. 3 – Well B RTHS and APWD comparison showing borehole washout while drilling 12¼-in. interval.**

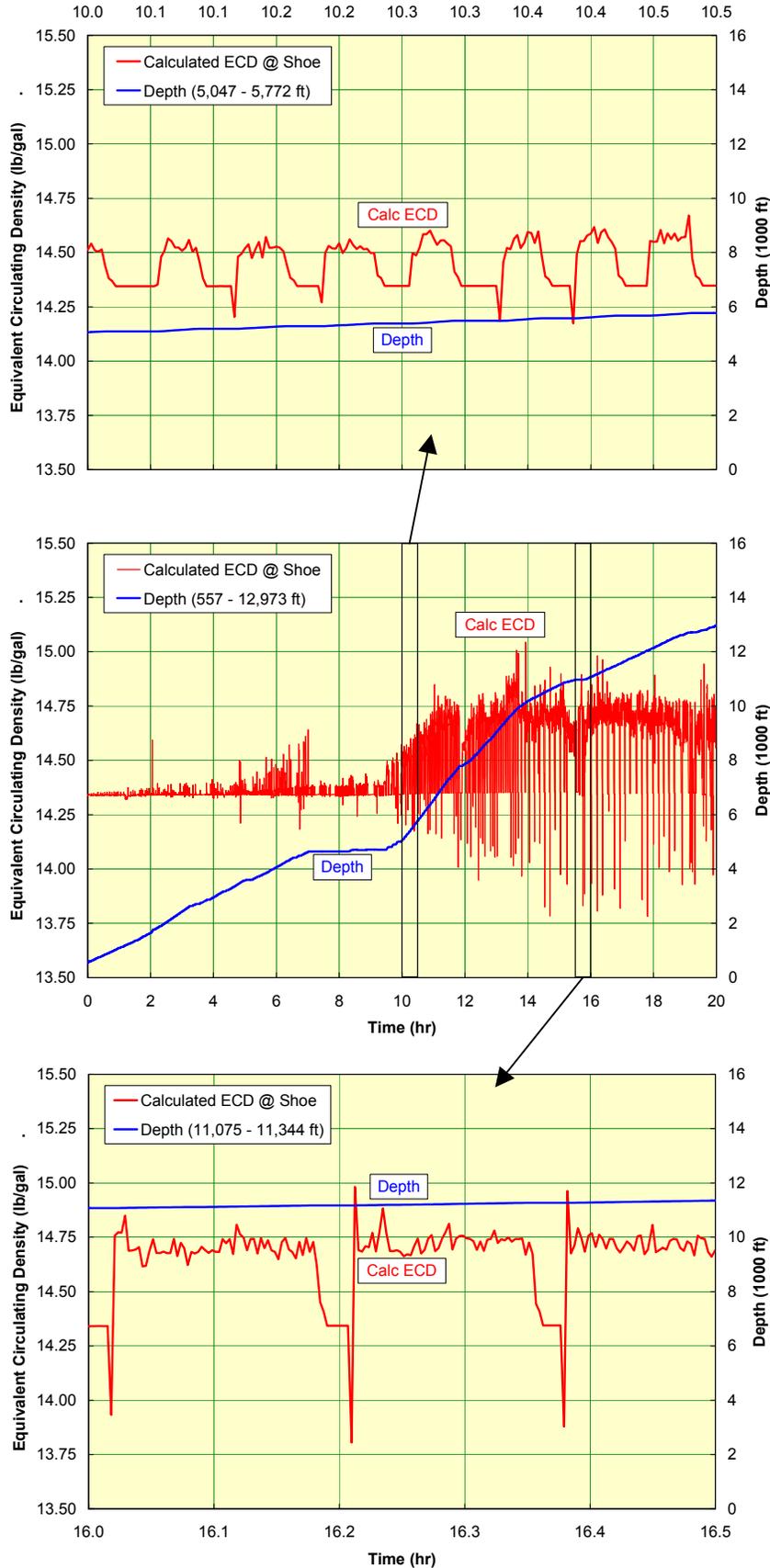**Fig. 4 – Well C RTHS and APWD from 13,847 to 14,523 ft immediately before kick.**

Fig. 5 – Well A RTHS calculated surge ECDs for 20-hr segment while running 9⅝-in. liner.