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Using True Real-Time Data Interpretation to Facilitate Deepwater Drilling

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Abstract

Significant challenges in deepwater drilling operations are exacerbated by narrow operating windows, especially when running synthetic-based muds in the cold-temperature environment. As such, downhole pressure measurements provided by PWD (pressure while drilling) have become virtually indispensable. Unfortunately, certain inherent characteristics of PWD technology can restrict or even prevent its application during critical operations. An advanced, real-time hydraulics system (RTHS) has been developed to complement and, in special cases, substitute for PWD. The RTHS, which has been used successfully in over seven exploratory wells in deepwater to 8,000 ft, is the subject of this paper.

The RTHS calculates downhole pressure, temperature, and hole-cleaning profiles in true real time based on surface-measured inputs. Calculated ECDs typically have been within 0.1 lb/gal of PWD values during normal drilling operations. In one case, a well-control situation was preceded by noticeable differences between measured and calculated downhole ECDs. In other cases, the RTHS has helped guide critical casing liner jobs in low-fracture-gradient environments. With no PWD tool installed, the RTHS was uniquely available to provide the instant feedback needed to minimize potentially serious problems.

The primary focus of this paper is RTHS deepwater case histories. Some discussion is included regarding basic modeling, hardware and software descriptions.

Introduction

The causes and severe consequences of hydraulics-related problems in deepwater drilling are well known.[1,2] Perhaps the most critical problems are associated with narrow operating windows, created at shallower depths by ultra-low fracture gradients and at deeper depths by convergence of formation pore and fracture pressures. Navigation through these narrow windows is exacerbated by the dramatic effects of low temperatures on mud density and rheological properties during drilling and especially when running casing.

Fig. 1 shows low-temperature PVT (pressure-volume-temperature) data taken on a Huxley-Bertram unit for an IO1618 fluid commonly used to formulate deepwater, synthetic-based muds (SBM). Originally built as a HTHP viscometer, the Huxley-Bertram design incorporates a floating piston mechanism that makes the device ideally suited for generating PVT data on base fluids and whole muds. **Fig. 2** presents temperature and pressure effects on basic rheological parameters of a 16.0-lb/gal IO1618 SBM as measured on a Fann Model 75 viscometer. Both test protocols call for circulating anti-freeze solution rather than water through the respective pressure cells for tests run colder than ambient temperature. The impact of cold temperatures experienced in deepwater is clearly demonstrated in the two figures. One consequence is that mud weights must be associated with the temperature at which they are measured. Another is that rheology on deepwater rigs is now routinely measured at three or more different temperatures and synchronized with Fann Model 70/75 tests run periodically in the lab.

Downhole conditions in deepwater wells (especially temperature) acting on the drilling fluid (especially SBMs) help create complex hydraulic situations and contribute to recurring drilling problems. Recent advancements in downhole hydraulics simulation[3] certainly have helped. Understandably, the application of PWD (pressure while drilling) to measure downhole pressures has become widespread and an essential part of ECD management in deepwater drilling. However, there are some inherent, indisputable limitations to current PWD technology.

PWD limitations have been targeted by a unique, first-generation computer system[4] developed specifically to complement (but not replace) PWD technology. The real-time hydraulics system (RTHS) leverages advanced hydraulics modeling and low-cost, high-powered computers. It can provide accurate ECD predictions that are of particular value when a PWD tool is not installed or has failed, or when measured data are not received at the surface in real time. If both data are available concurrently, such as during conventional drilling, well-site engineers can compare the PWD "what-is" and the RTHS "what-should-be" scenarios in order to make informed decisions and identify/prevent problems. Also, the RTHS generates surface-to-TD pressure profiles that augment the single-position data from the PWD tool and improve ECD predictions at the casing shoe.

True real-time hydraulics interpretation is applicable to all types of critical drilling projects[4,5], but is of particular benefit in the high-cost, technically challenging deepwater environment. The RTHS has been used successfully on one land and twelve offshore wells drilled in the US Gulf Coast, Norwegian sector of the North Sea, and the Nigerian continental shelf. Seven of these wells were drilled in deepwater from 2,100 to 8,000 ft, one by a floater and the other six by the same drillship. The primary goal of this paper is to present selected case history data from three deepwater Gulf of Mexico wells. The two wells drilled off Nigeria remain tight holes. Some discussion is devoted to RTHS basic modeling, hardware, and software concepts.

RTHS Description

The RTHS is a computer system that uses surface-measured input data to simulate in true real time the downhole hydraulics environment of water, oil, and synthetic-based fluids under extreme pressures and temperatures (low and high). "True" real time is achieved if results can be provided fast enough to actually affect changes in dynamic processes before their completion. While the acceptable time response for normal drilling can be minutes or even hours, drillstring connections and casing jobs require solutions in a matter of seconds for suitable action to be taken based on the results.

The software consists of two key parts - the underlying data acquisition/management system and the engineering modeling. The internal data management system is based on an event-driven, multi-threaded architecture that makes extensive use of low-level Windows API calls. Individual modules run concurrently and exchange information through shared global memory.

The comprehensive models used by the RTHS have previously been validated for offline use in various drilling applications.[3] Key considerations include, among others:

- temperature and pressure effects on downhole mud density based on a library of PVT data taken on commonly used base fluids,
- temperature and pressure effects on mud rheological properties based on Fann 35A and Fann 70/75 measurements,
- semi-steady-state and transient temperature profiles that consider complex geothermal profiles,
- multiple rheological models including Herschel-Bulkley, power law, Bingham plastic, and others,
- effect of constricted tool joints on frictional pressures,
- transient surge/swab pressures when running casing and tripping pipe,
- flow through special cement fill equipment for liner jobs, and
- fuzzy-logic, hole-cleaning analysis including effects of inclination, annular velocity, flow regime, mud type, mud properties, well geometry, eccentricity, pipe rotation, cuttings characteristics, transient cuttings concentration, and other parameters.

Considerations for transient behavior are required to adapt and update the models for use in real-time applications. If sensors are available to continuously measure inlet mud weight and temperature, the downhole density of each barrel of mud entering the hole can be dynamically tracked as it circulates throughout the well. This clearly is complicated by pipe movement and circulating off bottom. Realistic ESD and ECD (equivalent static and circulating densities, respectively) are then calculated based on transient temperature effects on density and rheological properties. The first circulation after the mud has been static for a period of time in deepwater is particularly critical.

The RTHS relies on a continuous stream of quality surface data (preferably at 1 Hz or faster) and periodic manual entries for data not measured by sensors. If available, some downhole measurements are also useful. For example, temperature measurements from PWD tools or from sensors installed on subsea stacks can be used to calibrate temperature simulations. PWD and subsea-stack pressures are helpful for comparison and interpretation, but are neither used nor required by the current calculation module.

Discrete RTHS results can be continually transmitted back into the rig's data pool within seconds after receiving input data. This allows results to be displayed at the driller's workstation as if they were measured, rather than calculated. ESD and ECD determined at the last casing shoe, total depth, and PWD-tool location are the most prominent results provided. The RTHS screen concurrently displays these and other measured, calculated, and interpreted parameters in graphics windows configured for drilling, tripping, and other operations. Four of these screens are illustrated in **Fig. 3**. Additional screens can easily be customized for special applications.

RTHS Installation

The RTHS uses a conventional Windows NT/2000 computer that typically is installed in the rig's mud lab or mud-logging unit. **Fig. 4** shows schematically how the RTHS can be added to an existing rig data-acquisition set up using the mud-logging unit as the central data source. On deepwater rigs, multiple data suppliers are required to continuously synchronize, share, and archive the high volume of measured and calculated data. Target data rate when the RTHS is involved is 1 Hz, but slightly slower speeds are acceptable in certain situations. For the deepwater wells on which the RTHS has been used, the most difficulties were encountered with initial setup and connectivity, including both hard-line connection and data-transfer synchronization.

Connectivity on the floater involved the mud-logging unit's proprietary data-transfer protocol using TCP/IP over an Ethernet LAN (local-area network). This approach was superior in terms of simplicity, efficiency, and performance. However, considerable effort was required to work with the data company (mud logging and PWD) to pre-install and validate their proprietary protocol on the RTHS computer.

The industry standard WITS[6] protocol was used on the drillship. Although a LAN was available, the mud logger at that time was unable to send WITS over TCP/IP. Instead, communications with the mud-logging unit were conducted serially over fiber-optic cable. Despite the thousands of feet of cable strung throughout the brand-new rig, initially there was no connection between the RTHS (in the mud lab) and the mud-logging unit. Running the fiber-optic cable proved to be particularly frustrating, primarily because of the circuitous path illustrated in **Fig. 5**, the rig crew's high work load during the initial rig shakedown, and numerous problems with connectors and cable integrity. The final cable connection covered several decks and much of the drillship's length.

In a typical installation, calculated RTHS results would be returned to the data source for updating rig-floor and other wellsite workstations. However, a shortage of serial ports made it more practical to send ESD and ECD values to the PWD unit over TCP/IP for subsequent distribution.

During the time the drillship was operating in the Gulf of Mexico, satellite communications allowed data exchange between the rig's RTHS computer and computers in the operator's office on land. Inexpensive, commercial communication software was used to transmit the RTHS screen directly onto an office computer every 2-3 sec. This information could have been accessed from any computer around the world that could login behind the operator's firewall. Also, the office computer could take control of the RTHS to remotely enter data, fix problems, update files, and conduct other conventional computer operations.

Most of the conventional rig sensors proved adequate. Pipe velocity and acceleration values, calculated from bit depth, and required for surge/swab pressures while running casing were suitable, with few data anomalies. The data-transfer rate can be critical if velocity and acceleration calculations are not made at or close to the bit depth sensor. Accurate density sensors were only available on one well to measure real-time mud weight in and out. Periodic manual entry of inlet mud weight was required on all other jobs. Clearly, sensitivity was much greater with accurate sensors, but real-time modeling results with simulated mud weight "in" values still were quite reasonable overall. Mud rheology (at multiple temperatures, and atmospheric and high pressures) also had to be entered manually, since practical inline viscometers are not yet available.

On occasion, problems were encountered with bit depth, one of the two critical variables used to synchronize data from different providers (the other is time). Accurate values were required for surge/swab calculations. Also, bit depth from one vendor was not consistently provided while making connections. During these short periods, it was impossible to calculate surge/swab pressures.

Case Histories

The seven exploratory deepwater wells on which the RTHS has been used are summarized chronologically in **Table 1** The first well was drilled from a floater in the Gulf of Mexico and the final six wells were drilled by the same deepwater drillship for three different operators.

Overall, calculated ECDs during drilling operations were typically within 0.1 lb/gal of PWD measurements when they were available. Calculated values substituted well for PWD when tools were not available or inoperable. Also, the RTHS helped guide several liner runs in narrow pressure-margin environments with minimal or controlled losses.

Case history data presented here are taken from three of the Gulf of Mexico wells – labeled C, D, and E in **Table 1** Unfortunately, no information can be released at this time on the Nigerian wells drilled in Blocks 217 and 218. Examples are provided to illustrate (a) how well RTHS predictions compared to PWD measurements, (b) calculated surge pressures while running casing, (c) use of RTHS to substitute for a failed PWD tool, and (d) transient hole cleaning and its effects on ECD. **Figs. 6-10** were drawn from Well D data; **Figs. 11-12** from Well E; and **Fig. 13** from Well C. Mud-weight and rheological properties are given in **Table 2** with reference to the figure number used in this paper. Note that all the muds were the same IO SBM that stayed with the drillship.

The following are general comments that apply to **Figs. 6-13**:

- PWD data (when shown on a graph) is unprocessed and does not include data that is stored but not transmitted to the surface in real time. These instances, easily recognized as straight, horizontal lines on the graphs, are usually under no-flow conditions.
- Much of the connection data during drilling sequences do not include surge/swab effects because instantaneous bit depths were not provided. However, the relatively "flat" lines during these periods reflect the calculated, real-time ESD plus cuttings. The associated PWD values should be ignored (see previous comment).
- RTHS ECD is calculated at the PWD tool location when both are provided on the same graph. Otherwise, the ECD is calculated at the last casing shoe depth.

Figs. 6-7, originally presented in a previous paper[4], are included here for comparison purposes and to correct certain details. The figures summarize operations in Well D to drill below 20-in. casing and run the 16-in. casing liner to 11,376 ft. The 20-in. casing shoe at 10,203 ft initially was tested to 9.65-lb/gal equivalent, and was subsequently retested to 10.0 lb/gal. The plan was to use PWD for ECD management while drilling the interval with a 20-in. bi-center bit and 9.0-lb/gal @ 58°F

SBM. Unfortunately, the tool was inoperable before starting to drill. Rather than trip in order to repair/replace the tool, the operator decided to rely on RTHS interpretations. **Fig. 6** is a plot of calculated ECDs at the shoe, penetration rates, and flow rates for a 10-hr portion of that interval. Because of ultra-low fracture gradients and indications from the RTHS of steadily increasing cuttings loading, penetration rates were controlled to reduce ECDs starting at the 3-hr mark on the figure. The noticeably uneven calculated ECD values reflect the transient hole-cleaning analysis (illustrated for a different well later in **Fig. 13**). Beyond the interval shown in the graph, lost circulation was encountered while circulating 9.6-lb/gal mud after a short trip, at which time it was decided to run casing.

Fig. 7 shows a 16-hr period of running the 16-in. casing liner in Well D. Between the 8 and 12-hr marks on the graph, casing was run at a gross average speed of 1,050 ft/hr with closed preventers and an open line to isolate weak zones downhole while saving running time. Surge pressures during this period, while artificial, still reflect the impact on the shoe that would have occurred with open preventers. Below the stack, the casing running speed was reduced to about 640 ft/hr to minimize losses, although they were still considerable.

Figs. 8-9 illustrate drilling the $14^3/_4$-in. interval and running $11^7/_8$-in. casing on Well D. The interval shown in **Fig. 8** from 11,956 to 13,096 ft was drilled at 200-300 ft/hr with 9.6-lb/gal SBM circulating at about 1,200 gal/min. Correlation between calculated ECD and PWD was very good. The maximum calculated ECD was 10.09 lb/gal; maximum measured PWD was 10.14 lb/gal. The average calculated ESD plus cuttings was 9.93 lb/gal. No hole problems were encountered until 14,857 ft where circulation was lost after weighting up to 10.2 lb/gal @52°F. Nearly 1,000 bbl of mud were lost cumulatively before running casing to 14,814 ft. **Fig. 9** is the surge/swab graph for the interval of 1,583 to 13,422 ft. Mud losses averaged 20 bbl/jt, but the casing was successfully run and cemented.

Fig. 10 presents results from drilling in Well D the $12^1/_4$-in. section with a bi-center bit. Penetration rates were about 100 ft/hr for the 17,361 to 17,991 ft interval shown on the graph. Agreement between calculated ECD and PWD measurements was excellent, ranging over the interval from 10.80 to 10.87 lb/gal and 10.81 to 10.90 lb/gal, respectively. The previous shoe was tested to 11.4 lb/gal. The complete interval was drilled with no problems.

Fig. 11 compares PWD and RTHS results while drilling the 17-in. interval in Well E with a bi-center bit. The interval on the graph is from 12,189 to 12,854 ft. A 16-in. casing liner had been set at 11,565 ft. No drilling problems were encountered in this hole interval. Average mud weight for the SBM was 9.9 lb/gal @ 61°F; maximum ECDs at the PWD-tool location were measured at 10.4 lb/gal and calculated at 10.36 lb/gal. The ESD plus cuttings averaged just below 10.2 lb/gal.

Fig. 12 data were generated while drilling the $14^3/_4$-in. interval in Well E. Agreement was excellent between PWD and RTHS results for the first 4 hr on the graph. Penetration rates ranged from 100 to 200 ft/hr. The calculated increase in annular pressure averaged 0.29 lb/gal while circulating the 11.0-lb/gal @60°F SBM at about 1,100 gal/min. The swivel packing was replaced during the 4 and 5.5-hr time interval on **Fig. 12**. Drilling resumed until the well was shut-in on a gas kick at 14,523 ft, close to the 9-hr time mark. Note the variance between calculated and measured ECDs immediately preceding the kick. Unfortunately, this was not picked up at the time, despite the concurrence of other conventional kick-detection parameters.

Fig. 13 demonstrates how the RTHS software handles transient hole cleaning and illustrates the impact on the ECD profile. The series of graphs represent a 2-hr 13-min time sequence from Well C just below 10,000 ft. A 17-in. bi-center bit was used to drill out an $8^1/_2$-in. pilot hole. Penetration rate was about 150 ft/hr; flow rate was 1,100 gal/min. The hole was fairly clean prior to start of the sequence after conducting coring operations.

Hole-cleaning performance is indicated by a fuzzy logic index where values to the left represent very good cleaning and values to the extreme right represent very poor cleaning. In this vertical interval, the hole-cleaning index was closely related to the cuttings concentration in the annulus. The ECD scale is 9.5 to 9.8 lb/gal. Note how newly generated cuttings were circulated up the well and somewhat redistributed by the drilling process. The impact on the ECD profile also is evident. The slight lateral shifts in ECD curves were caused by changing annular temperature profiles.

Conclusions

1. True real-time interpretation of downhole hydraulics has been successfully applied in seven exploratory wells in deepwater to 8,000 ft in the Gulf of Mexico and Nigeria continental shelf.
2. This first-generation technology has helped facilitate deepwater drilling by complementing PWD, and even substituting for PWD when data were neither available nor transmitted to surface in real time.
3. Downhole ECDs were consistently calculated in real time to within 0.1 lb/gal of measured values during normal drilling operations.
4. Real-time, surge-pressure calculations were uniquely available to guide casing operations, because no other tools were available to determine the combined effects of transient downhole hydraulics and pipe dynamics.
5. While most conventional rig sensors proved adequate, hydraulics interpretation was improved on one well by the use of an inline sensor to measure real-time mud weight (in and out).
6. Greatest difficulties with the new computer system have been encountered with initial setup and connectivity, including both hard-line connection and data-transfer synchronization.

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6. *WITS - Wellsite Information Transfer System Implementation Guideline*, API Publication 3855, version 1.1 (July 1991).

Table 1
RTHS Deepwater Case Histories

Well ID	Location	Water Depth (ft)	Rig Type
A	Gulf of Mexico	2,100	Floater
B	Gulf of Mexico	6,663	Drillship
C	Gulf of Mexico	7,212	Drillship
D	Gulf of Mexico	8,000	Drillship
E	Gulf of Mexico	6,286	Drillship
F	Nigeria CS	4,793	Drillship
G	Nigeria CS	4,200	Drillship

Table 2- Mud Type/Weight and Fann 35A Rheological Properties by Figure Number

Parameter	Fig. 6	Fig. 7	Fig. 8	Fig. 9	Fig. 10	Fig. 11	Fig. 12	Fig. 13
Mud Type	IO SBM	IO SBM	IO SBM	IO SBM	IO SBM	IO SBM	IO SBM	IO SBM
S/W Ratio	69/31	72/28	69/31	67/33	70/30	72/28	69/31	73/27
Density (lb/gal)	9.0	9.6	9.6	10.2	10.4	9.9	11.0	9.45
Density Temp (°F)	58	78	53	54	60	61	60	50
Rheology Temp (°F)	150	150	150	150	150	150	150	150
R600	46	52	55	52	50	52	57	42
R300	31	33	39	34	33	34	38	27
R200	25	26	32	27	26	24	30	22
R100	18	17	24	18	19	16	25	17
R6	11	10	14	14	8	10	19	11
R3	10	9	13	12	7	9	17	10
10s Gel	12	9	14	14	16	14	24	6
10m Gel	17	12	19	16	21	18	28	11

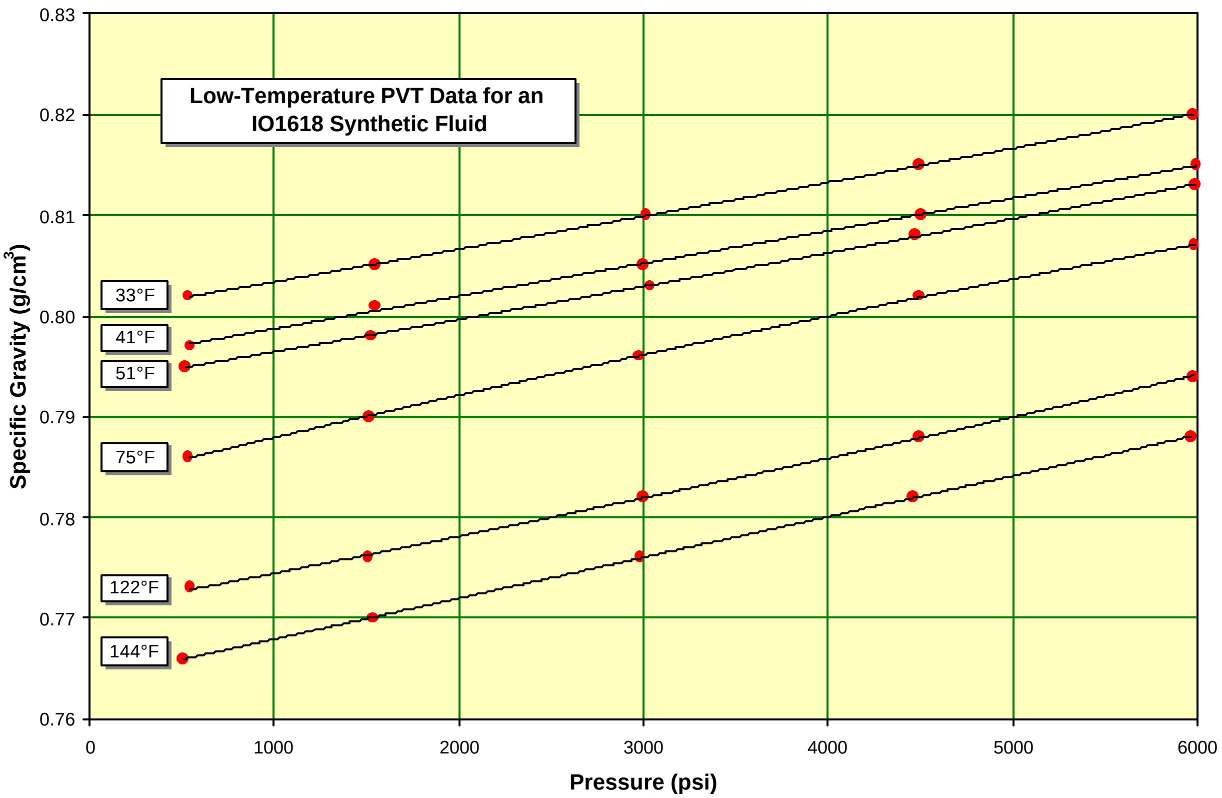

Fig. 1 - Low-temperature PVT data for an IO1618 synthetic fluid run on a Huxley-Bertram HTHP viscometer.

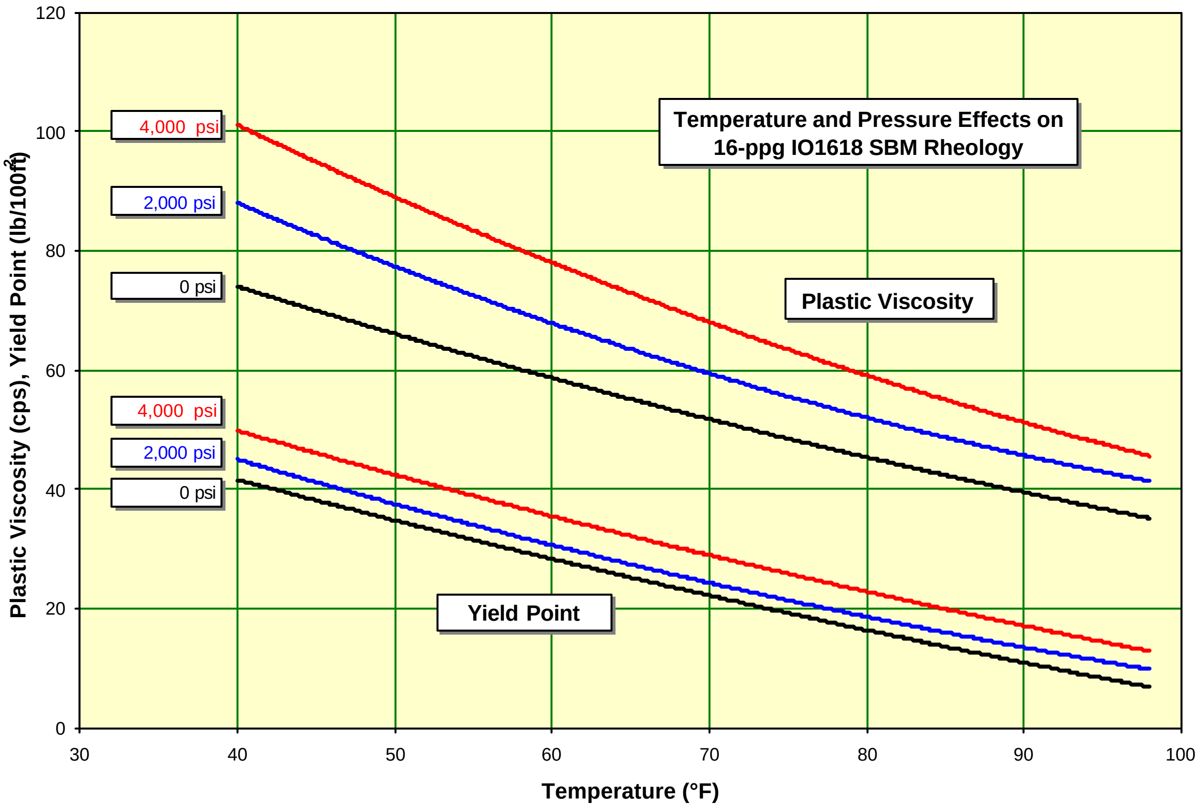

Fig. 2 – Low-temperature and pressure effects on PV and YP of a 16-lb/gal, 85/15 SWR IO1618 synthetic-based mud.

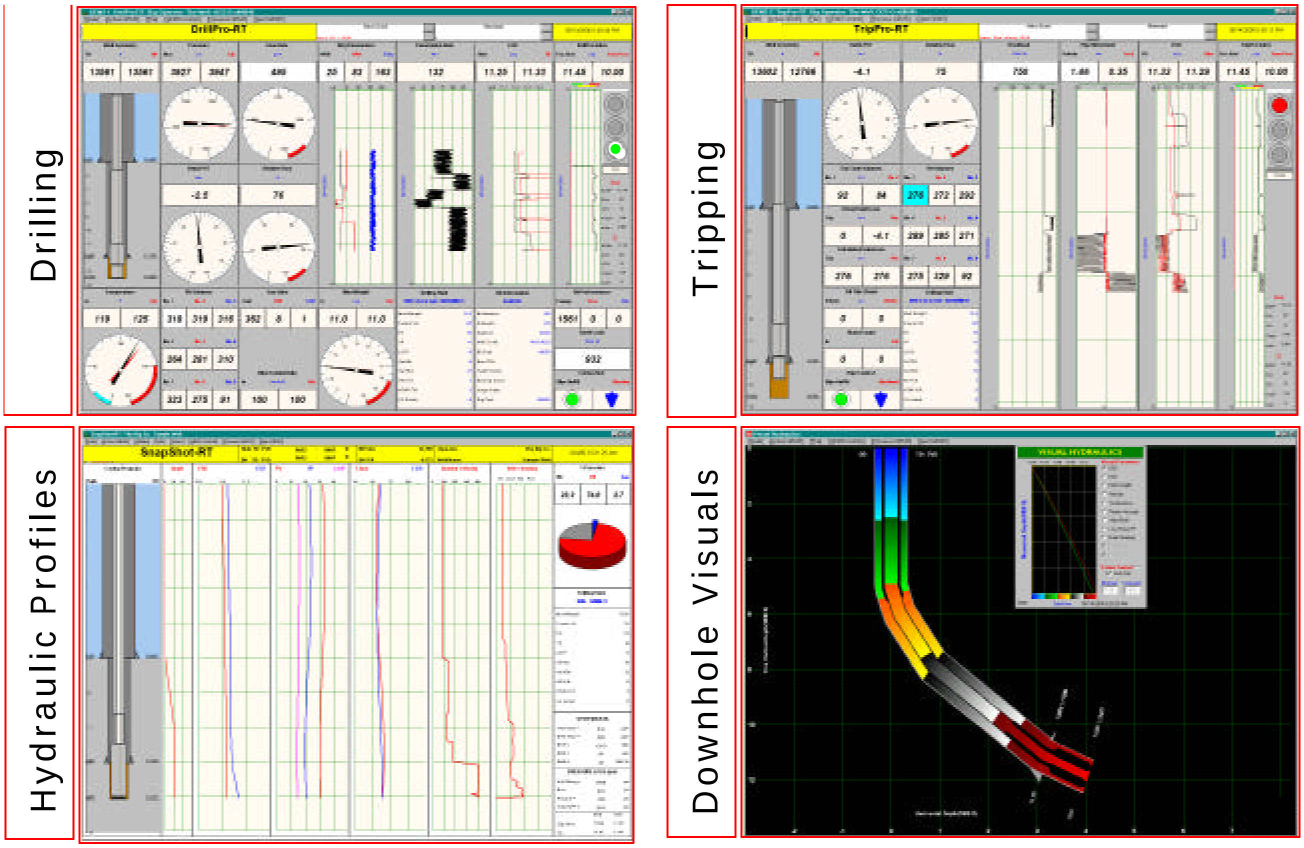

Fig. 3 - Example RTHS display screens for different operations.

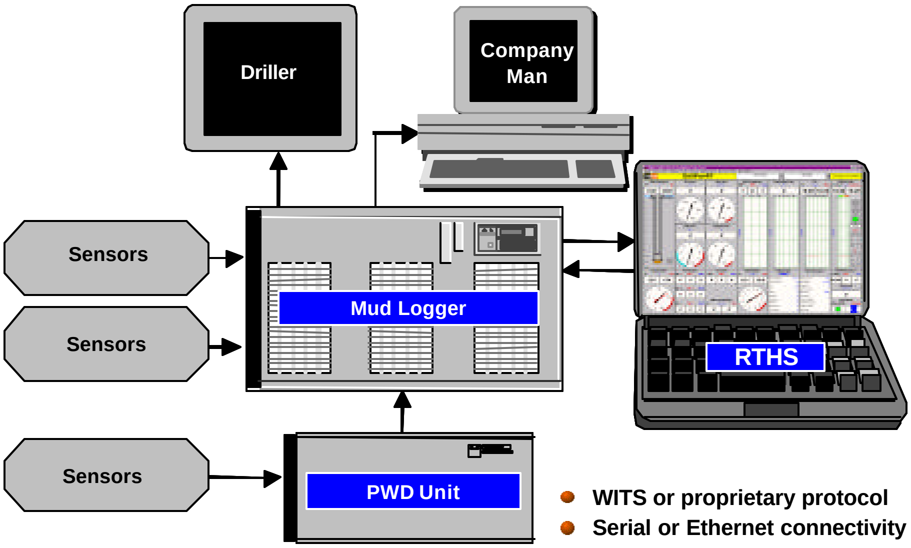

Fig. 4 - Typical RTHS installation on deepwater projects.

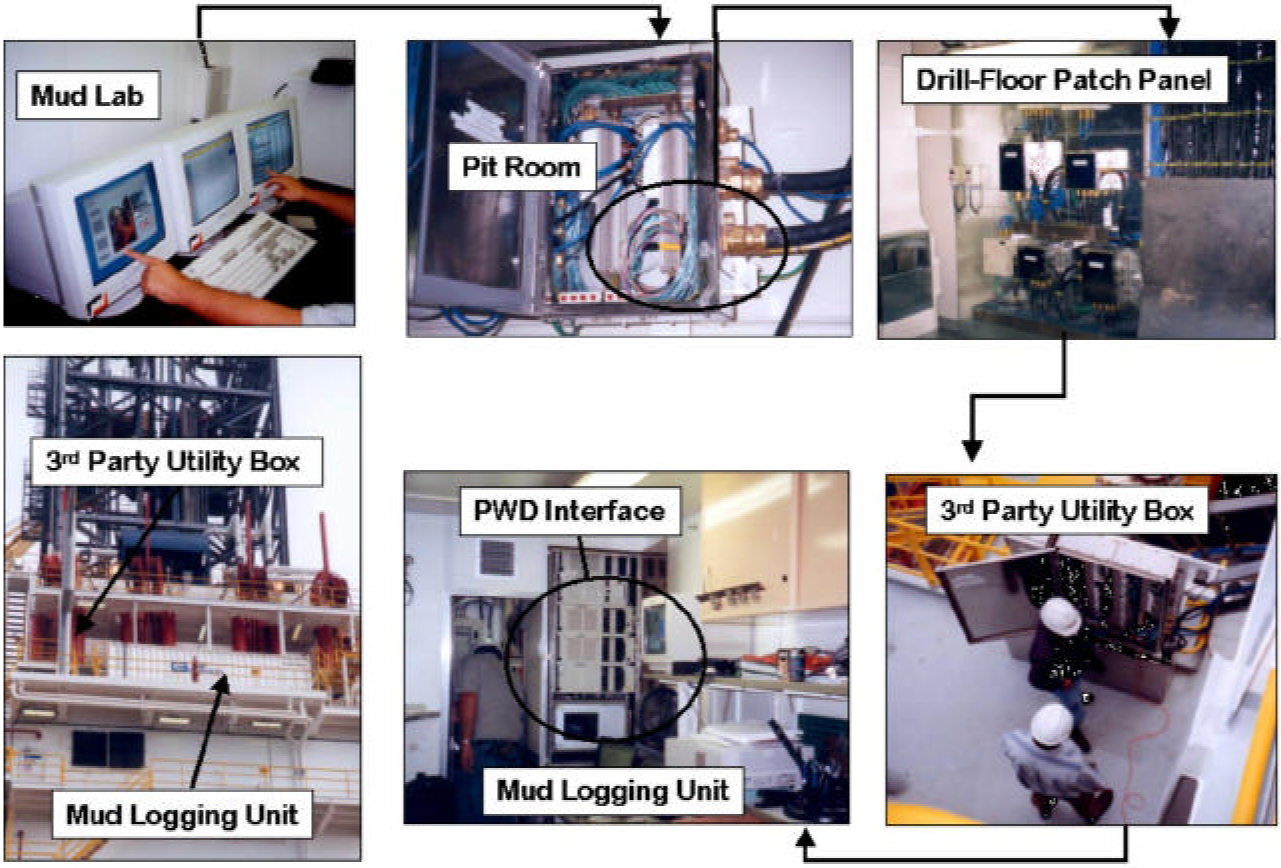

Fig. 5 - Complex fiber-optic cable connection from RTHS in mud lab to mud-logger data source.

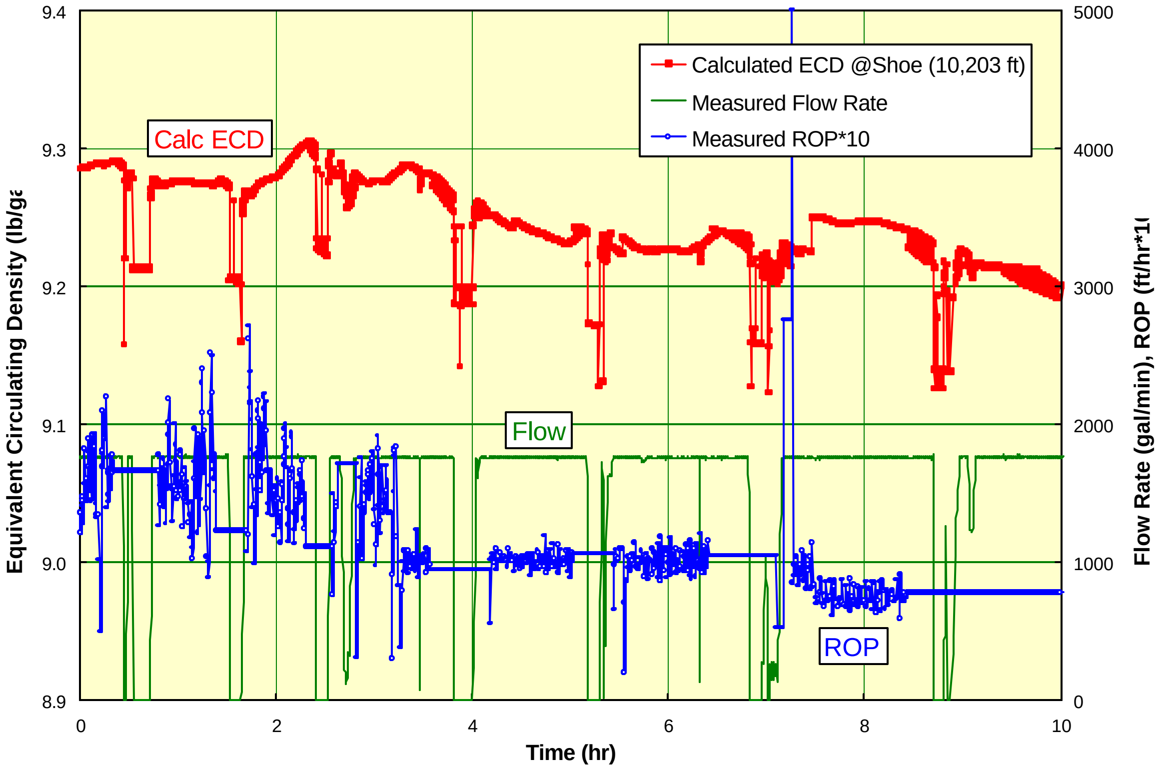

Fig. 6 - Calculated ECDs at the casing shoe, penetration rates, and flow rates while drilling on Well D.

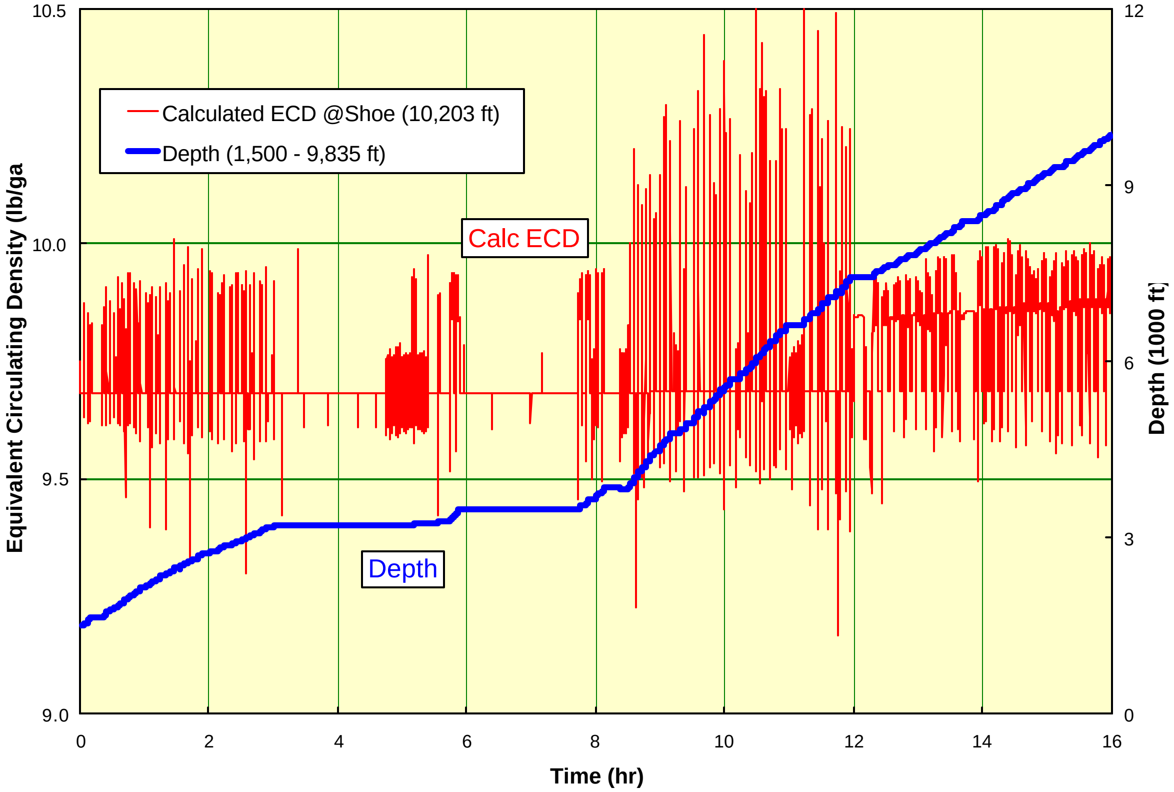

Fig. 7 - RTHS-calculated surge ECDs for a 16-hr segment while running a casing liner in Well D.

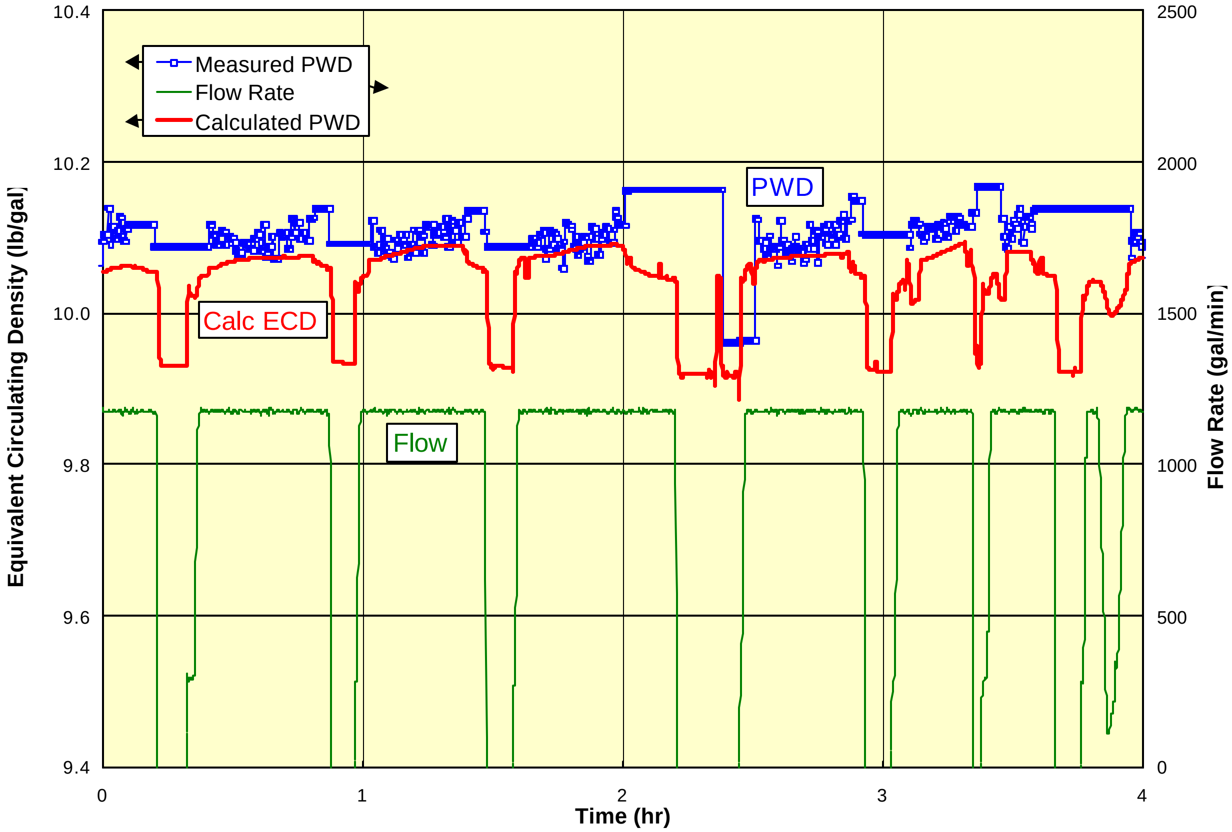

Fig. 8 - Well D RTHS and PWD comparison while drilling $14^3/_4$-in. interval from 11,956 to 13,096 ft.

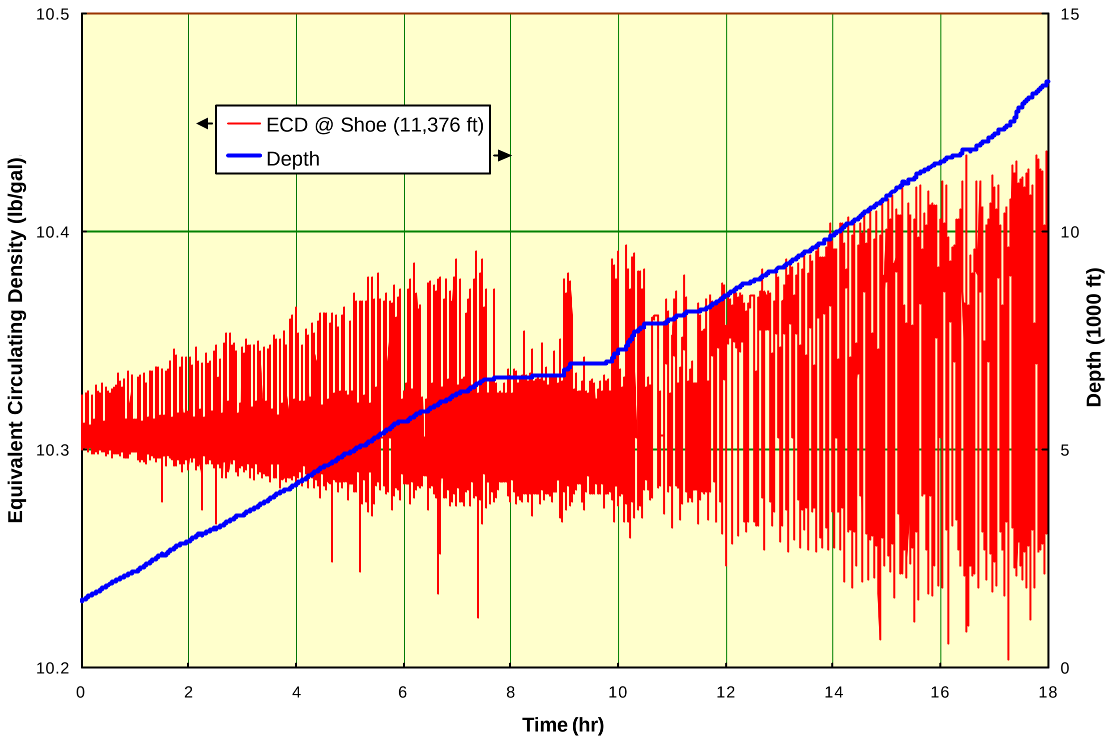

Fig. 9 - Well D surge/swab pressures while running 11$^7/_8$-in. casing from1,583 to 13,422 ft.

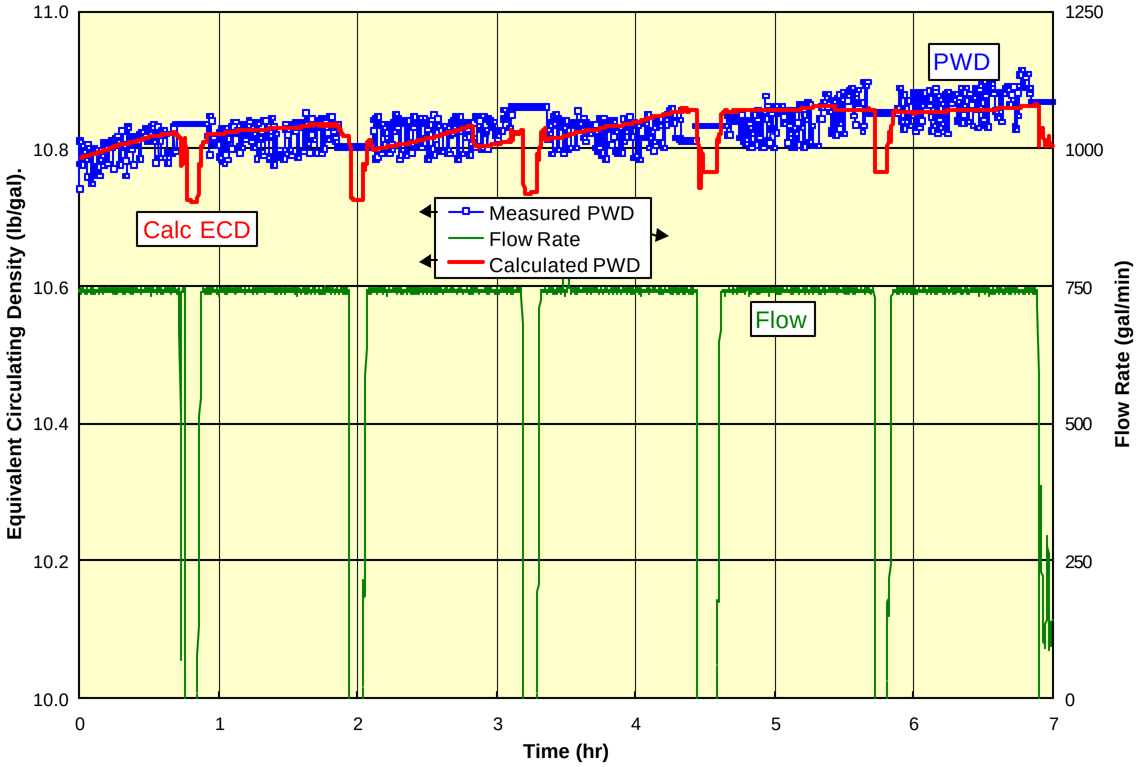

Fig. 10 - Drilling 12$^1/_4$-in. interval 17,361 ft to 17,991 ft on Well D.

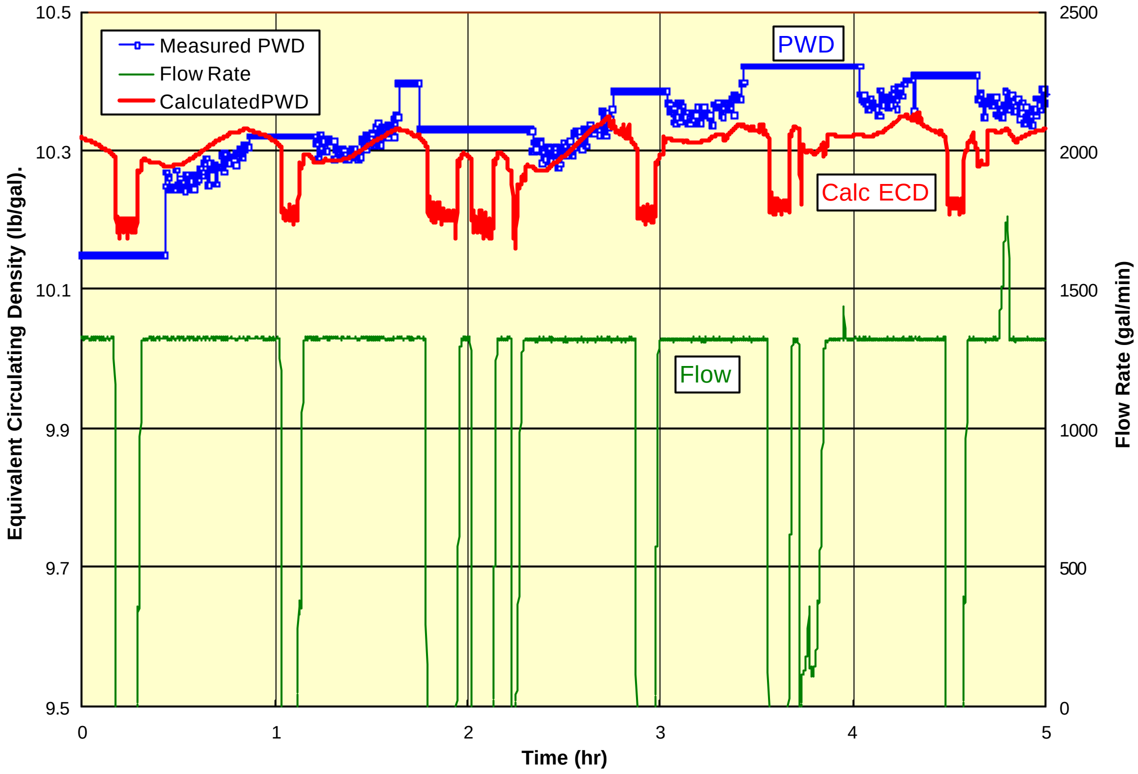

Fig. 11 - Drilling 17-in. interval on Well E from 12,189 to 12,854 ft.

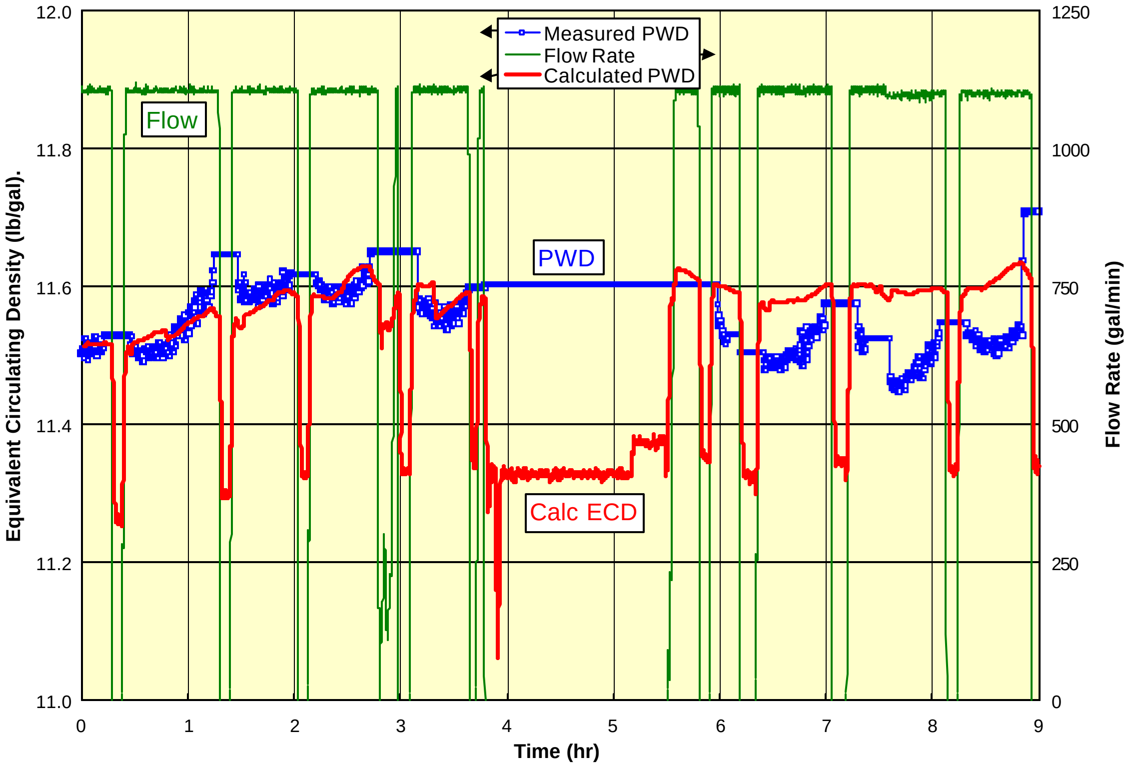

Fig. 12 - Drilling $14^3/_4$-in. section on Well E from 13,847 to 14,523 ft immediately before kick.

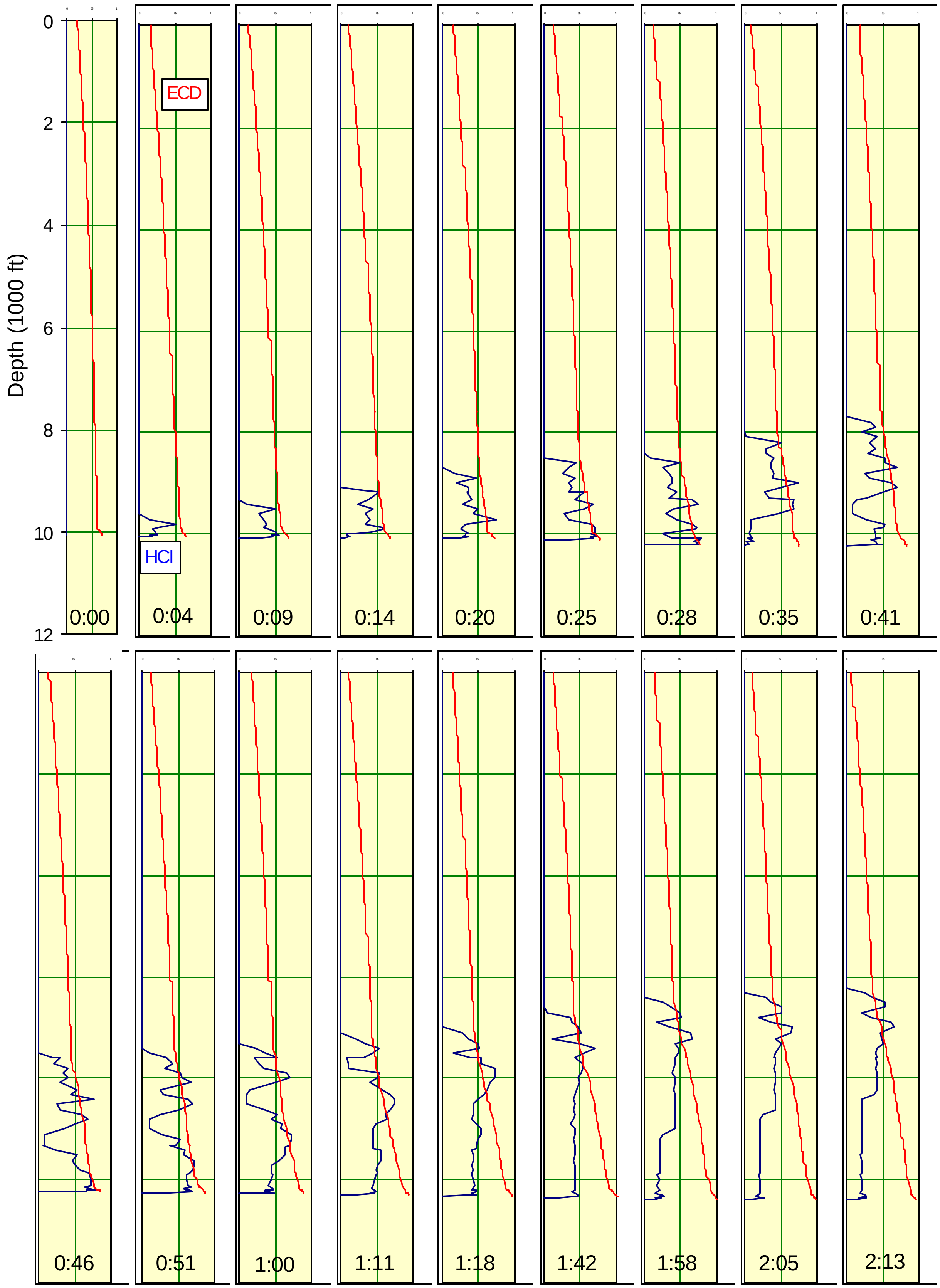

Fig. 13 - 2:13 hr sequence of ECD and hole-cleaning index profiles for Well C in 17-in. hole drilled through an $8^1/_2$-in. pilot hole.