Effects of p-ρ-T Behavior of Muds on Static Pressures During Deep Well Drilling

D.R. Babu,* SPE, Oil India Ltd.

27419

Summary

In this study, published p-ρ-T data of twelve muds are compared using three models already proposed. The empirical model suggested by Kutasov is found to represent the measured data more accurately than the other models for a majority of the muds. With the help of the empirical model, an explicit equation is derived analytically to predict static pressures at different depths. Based on the analysis, an equivalent static density (ESD) variable is defined that incorporates the mud p-ρ-T behavior, pressure and temperature of the mud at surface, thermal gradient, and depth of the well. It is suggested that ESD should be used in place of normally used mud weight term in all phases of deep well drilling. The analysis is applied to a high-temperature, 25,000-ft deep example well. It is observed that static pressure or ESD at the bottom of the well decreases during tripping and the extent of decrease is dependent on the type of mud. For the example well, it is estimated that a maximum reduction in ESD of about 0.62 lbm/gal occurs in the case of 18-lbm/gal water-based-mud, and a minimum reduction of about 0.2 lbm/gal occurs in the case of a 11-lbm/gal diesel-oil-based mud.

Introduction

During various phases of drilling, static pressures exerted by a mud column are usually calculated by assuming a constant mud weight at all depths in the borehole. Mud at different depths experiences different temperatures and pressures. Further, the temperature in the borehole changes during different phases of drilling. Mud weights at downhole temperatures and pressures can be significantly different from those measured at the surface in high-pressure and high-temperature (HPHT) deep wells. Measured data[1,2] of different muds whose weights varied up to 18 lbm/gal and temperatures up to 400°F and pressures up to 15,000 psig showed that mud weight variations of the magnitude of 1.5 lbm/gal occurred for both water- as well as oil-based muds. If these variations are not accounted properly during the estimation of static pressures, they can cause well control problems during deep and hot well drilling. Through a recent survey conducted in the Norwegian sector of North Sea oil fields, Mathiesen[3] observed HPHT deep wells were prone to more kicks and well-control problems when compared to the other deep wells drilled in the same area.

In the past, two numerical models[4,5] were proposed to estimate the static pressures while accounting for the mud weight variations with downhole pressures and temperatures. Because these models are based on the compositions of the muds, they require large data bases of p-ρ-T behaviors of individual components. Currently, there is no simple and accurate method available for the industry for the estimation of downhole static pressures that incorporates the p-ρ-T behavior of muds.

Evaluation of p-ρ-T Models of Drilling Muds

In the past, several authors[2,4,6] proposed compositional models to interpret p-ρ-T behavior of drilling muds. In the compositional models, the density of solids is assumed to be independent of temperature and pressure and the p-ρ-T behavior of mud is interpreted in terms of changing densities of liquid phases. It is also assumed that there are no physicochemical interactions between solids and liquid. If ρ_m, ρ_w, and ρ_h are the densities of mud, water, and hydrocarbon phases respectively at any pressure p and temperature T, then the compositional model[2] is given by

$$\rho_m = \frac{\rho_{m1}}{1 + V_{fw1}\left(\frac{\rho_{w1}}{\rho_w} - 1\right) + V_{fh1}\left(\frac{\rho_{h1}}{\rho_h} - 1\right)} \quad \text{.......... (1)}$$

The subscript "1" indicates the values at a temperature of T_1 and pressure p_1, and V_{fw1} and V_{fh1} are the fractional volumes of water and hydrocarbon phases, respectively. McMordie *et al.*[1] and Peters *et al.*[2] reported p-ρ-T data for twelve muds using HPHT autoclaves. Peters *et al.*[2] satisfactorily predicted mud weights with Eq. 1, using ρ_h and ρ_w data obtained on the same equipment. Sorelle *et al.*[6] proposed the following relationships for ρ_w and ρ_h (diesel oil No. 2) for use in Eq. 1.

$$\rho_w = 8.63186 - 3.31977 \times 10^{-3}T + 2.3717 \times 10^{-5}(p - p_0), \quad \text{....... (2)}$$

$$\rho_h = 7.24032 - 2.84383 \times 10^{-3}T + 2.7566 \times 10^{-5}(p - p_0). \quad \text{....... (3)}$$

Kutasov[7] analyzed p-ρ-T behavior of water and proposed the following relationship.

$$\rho_w = 8.3619\exp[3.0997 \times 10^{-6}(p - p_0) - 2.2139 \times 10^{-4}(T - T_0) - 5.0123 \times 10^{-7}(T - T_0)^2]. \quad \text{....... (4)}$$

The average error in predicting the water densities with Eq. 4 in the HPHT region was reported to be low. Using Eq.4, Babu[8] studied the effect of thermal gradient on hydrostatic gradients. In the above equations, p_0 and T_0 represent standard pressure (14.7 psia) and temperature (59°F), respectively.

Predicted values of mud weights were computed for the Sorelle *et al.*[6] model using Eqs. 1 through 3, and the average errors are given in **Table 1** for three water-based muds and for three oil-based muds of McMordie *et al.*[1] (Muds 1 through 6) and for two oil-based muds of Peters *et al.*[2] (Muds 7 and 8). The average error is computed as

$$\text{Average Error} = \frac{\sum_{1}^{N} \frac{|\rho_{meas} - \rho_{pred}|}{\rho_{meas}}}{N}. \quad \text{....... (5)}$$

It may be noted these five oil-based muds (i.e., Muds 4 through 8) were prepared from diesel oil No. 2. Because Eq. 4 represented the water density data accurately, mud weights predicted from Eq. 1 and Eq. 4 are computed for three water-based muds and the average errors are given in Table 1 under compositional model. For all the cases, for use in Eq. 1, measured mud weights at the lowest temperature and at atmospheric pressure were used as ρ_{m1}. Corresponding V_{fw1} and V_{fh1} values were estimated from the compositions of the individual muds reported in the respective studies. Average errors calculated from the tables of predicted and measured mud weights of Peters *et al.*[2] for six oil-based muds are also given in Table 1 as compositional model.

Kutasov[9] proposed the following empirical equation to describe the p-ρ-T behavior of drilling muds.

$$\rho_m = \rho_{m0}\exp[\alpha(p - p_0) - \beta(T - T_0) \pm \gamma(T - T_0)^2]. \quad \text{.. (6)}$$

*Now with Engineers India Ltd.

Original SPE manuscript received for review Aug. 10, 1993. Revised manuscript received Nov. 29, 1995. Paper (SPE 27419) peer approved Jan. 24, 1996.

TABLE 1—COMPARISON OF AVERAGE ERRORS BETWEEN THE THREE MODELS

Mud No.	Base of Mud	Mud Wt. in lbm/gal	Sorelle *et al.*	Average Error in % Compositional	Empirical
1	Water	11	1.31	0.38	0.19
2	Water	14	1.15	0.41	0.12
3	Water	18	1.43	0.80	0.11
4	Diesel Oil No. 2	11	1.35	NA	0.25
5	Diesel Oil No. 2	14	1.36	NA	0.18
6	Diesel Oil No. 2	18	1.29	NA	0.17
7	Diesel Oil No. 2	11	0.49	0.27	0.27
8	Diesel Oil No. 2	17	0.50	0.23	0.23
9	Mineral Oil-A	11	NA	0.28	0.31
10	Mineral Oil-A	17	NA	0.16	0.24
11	Mineral Oil-B	11	NA	0.17	0.33
12	Mineral Oil-B	17	NA	0.10	0.27

Muds 1 through 6 from McMordie *et al.*[1]
Muds 7 through 12 from Peters *et al.*[2]
NA - Not available

He evaluated the empirical constants ρ_{m0}, α, β, and γ for the measured data for five muds (Muds 1 through 4 and 6) of McMordie *et al.*[1] The constants are given in **Table 2.** Linear regression analysis performed on the measured data of Mud 5 yielded empirical constants that were different from those given by Kutasov.[9] These constants are given in Table 2, which predicted the measured mud weights with an average error of 0.18%, which is marginally better than 0.21% obtained by using the constants suggested by Kutasov.[9]

Empirical constants for the six oil-based muds of Peters *et al.*[2] (Muds 7 through 12) were estimated and given in Table 2. The average errors in the predicted values of Eq. 6 for the twelve muds are given in Table 1. Predicted mud weights with the empirical model are compared with those in the other models in **Figs. 1 through 3** for Muds 3, 4, and 7, respectively.

TABLE 2—EMPIRICAL CONSTANTS IN EQ. 6 FOR DIFFERENT MUDS

Mud No.	Base of Mud	ρ_{m0} lbm/gal	α x10^6 psi^{-1}	β x10^4 °F^{-1}	γ x10^7 °F^{-2}
1	Water	10.770	3.3815	2.3489	−4.2366
2	Water	13.684	3.2976	1.7702	−5.2126
3	Water	18.079	3.0296	1.3547	−4.1444
4	Diesel Oil No. 2	11.020	6.5146	4.3414	1.4144
5	Diesel Oil No. 2	14.310	5.9793	3.3701	0.3383
6	Diesel Oil No. 2	18.049	5.1951	2.9637	0.7460
7	Diesel Oil No. 2	11.042	3.3807	3.6838	1.8996
8	Diesel Oil No. 2	17.030	2.7186	2.5544	1.0479
9	Mineral Oil-A	11.029	3.9462	3.5364	1.2184
10	Mineral Oil-A	17.028	2.8496	2.4840	0.1884
11	Mineral Oil-B	11.033	4.0659	3.7981	1.8033
12	Mineral Oil-B	17.032	2.9796	2.6558	0.8413

Constants for Muds 1 through 4 and 6 are estimated by Kutasov.[9]

Constant Mud Weight in the Well

While computing the mud weight profiles in the wells, Peters *et al.*[2] observed that in a cold well, mud weight increased with depth and the opposite occurred in a hot well. They concluded that *a priori* prediction of how the downhole mud weights vary was not possible. With the help of the empirical model given in Eq. 6, such *a priori* predictions can be made very easily. Because the temperature and pressure of a mud column increases with depth, the mud at any depth experiences two opposing effects. Increase in pressure tends to increase the mud weight because of compressibility, whereas the increase in temperature tends to decrease the mud weight owing to thermal expansion. For a particular temperature profile, these two opposite effects cancel out, leaving uniform mud weight along the depth of the well that is equal to that at surface, i.e., ρ_{m0}. For this to occur, the argument of the exponential term in Eq. 6 should be zero, i.e.,

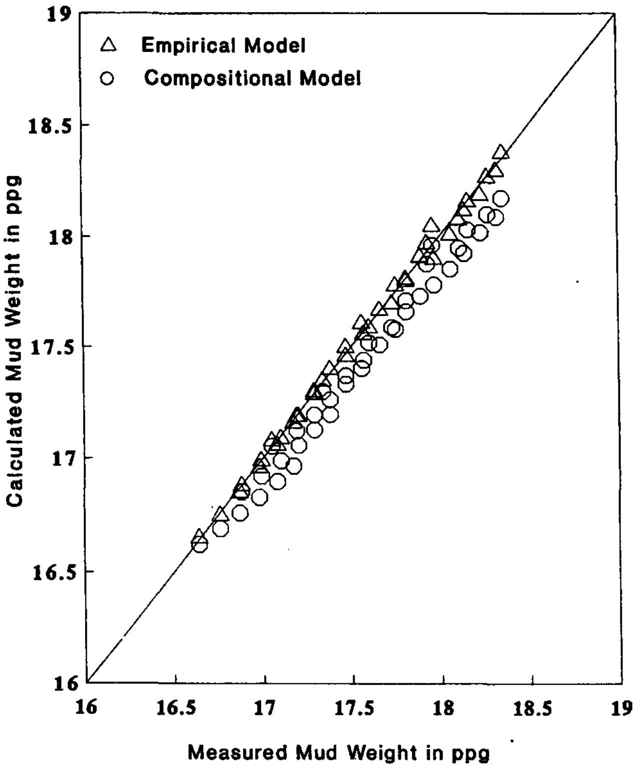

Fig. 1—Comparison of calculated and measured mud weights for 18-lbm/gal water-based mud (Mud 3).

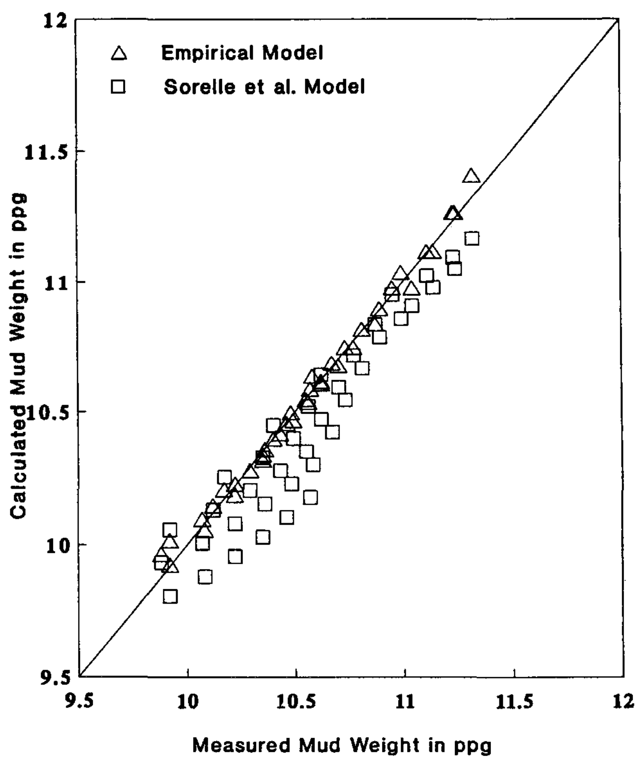

Fig. 2—Comparison of calculated and measured mud weights for 11-lbm/gal diesel-oil-based mud (Mud 4).

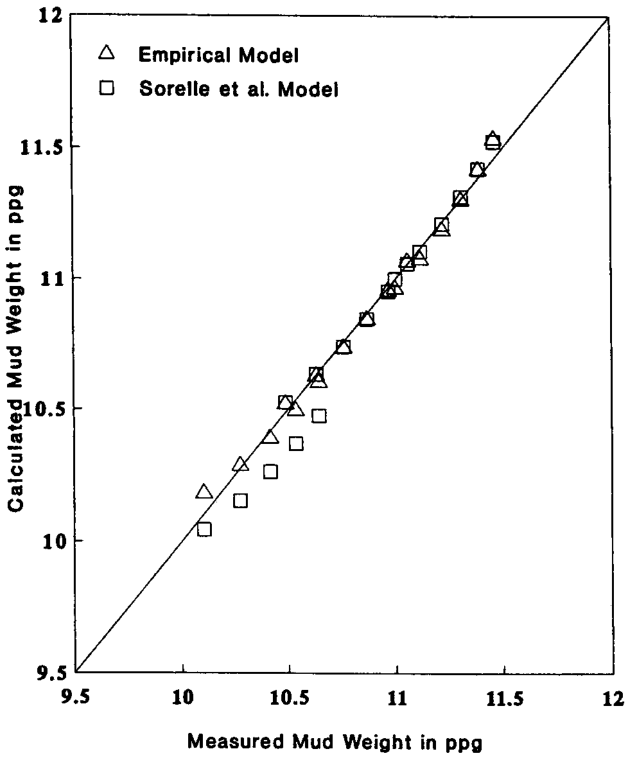

Fig. 3—Comparison of calculated and measured mud weights for 11-lbm/gal diesel-oil-based mud (Mud 7).

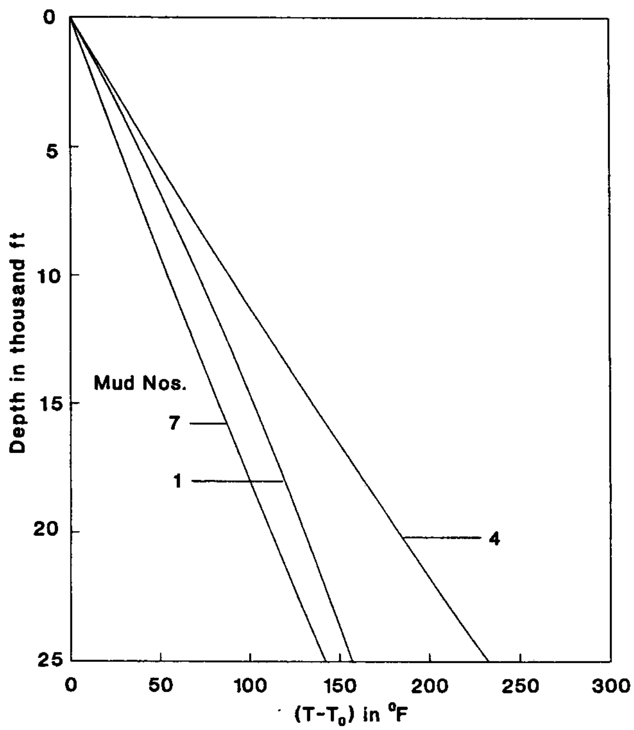

Fig. 4—Temperature profiles for constant mud weight condition for three 11-lbm/gal muds (Muds 1, 4 and 7).

$$\alpha(p - p_0) - \beta(T - T_0) \pm \gamma(T - T_0)^2 = 0. \qquad (7)$$

In such situation, the pressure at any depth is given by

$$p - p_0 = 0.052\,\rho_{m0}\,D. \qquad (8)$$

After substituting Eq. 8, Eq. 7 can be solved to get an explicit relation for T in terms of D.

$$T - T_0 = \frac{\beta - \sqrt{\beta^2 \mp 0.208\,\alpha\,\gamma\,\rho_{m0}\,D}}{\pm\, 2\gamma}. \qquad (9)$$

It is interpreted that when a mud at a particular depth has a temperature higher than that given by Eq. 9, the mud weight at that depth is lower than that measured at the surface, which shows the dominance of thermal expansion effect. If the temperature of the mud is lower, then the mud weight is higher than that measured at the surface, which indicates that the compressibility effect is predominant. Using the empirical constants given in Table 2, the temperatures pre-dicted by Eq. 9 are plotted against depth for Muds 1, 4, and 7 in **Fig. 4.**

Estimation of Static Pressures

To get an analytical solution, a simplified version of mechanical energy balance can be written as

$$\frac{dp}{dD} = 0.052\rho_m. \qquad (10)$$

It is assumed that the temperature of borehole increases linearly with depth, i.e.,

$$T = T_0 + g_T D. \qquad (11)$$

The boundary condition at the surface can be written as

$$\text{at } D = 0;\; p = p_0,\; T = T_0. \qquad (12)$$

After substituting Eq. 6 and Eq. 11 in Eq. 10 and solving it with appropriate manipulations and with the help of the boundary conditions given by Eq. 12, one gets

$$p - p_0 = \frac{1}{\alpha}\ln\frac{1}{1 - F(D)}. \qquad (13)$$

In this equation, the function $F(D)$ assumes two different forms, depending upon the sign of the $\gamma(T-T_0)^2$ term of Eq. 6.

In most of the fields, pressure is conveniently represented as pressure gradient expressed in density units. Therefore, an ESD or ρ_{se} variable that incorporates p-ρ-T behavior of the mud, surface temperature and pressure, thermal gradient, and depth of the well can be defined as

$$ESD = \frac{p - p_0}{0.052D} = \frac{1}{0.052\alpha D}\ln\frac{1}{1 - F(D)}. \qquad (14)$$

ESD can be used in place of normally used mud weight term to have a better understanding of several critical drilling situations.

Case 1

For oil-based muds, the p-ρ-T relationship is given by

$$\rho_m = \rho_{m0}\exp[\alpha(p - p_0) - \beta(T - T_0) + \gamma(T - T_0)^2]. \qquad (15)$$

For this case, $F(D)$ assumes the following form.

$$F(D) = \frac{0.052\alpha\rho_{m0}\exp(-a^2)}{\sqrt{\gamma}\,g_T}\sum_{k=0}^{\infty}\frac{D_{D1}{}^{2k+1} + a^{2k+1}}{(2k+1)k!}, \qquad (16)$$

where the dimensionless constant a is given by

$$a = \frac{\beta}{2\sqrt{\gamma}}, \qquad (17)$$

and the dimensionless depth variable D_{D1} is given by

$$D_{D1} = \sqrt{\gamma}\,g_T D - a. \qquad (18)$$

For field applications, summation of the convergent series in Eq. 16 over the first ten terms gives enough accuracy.

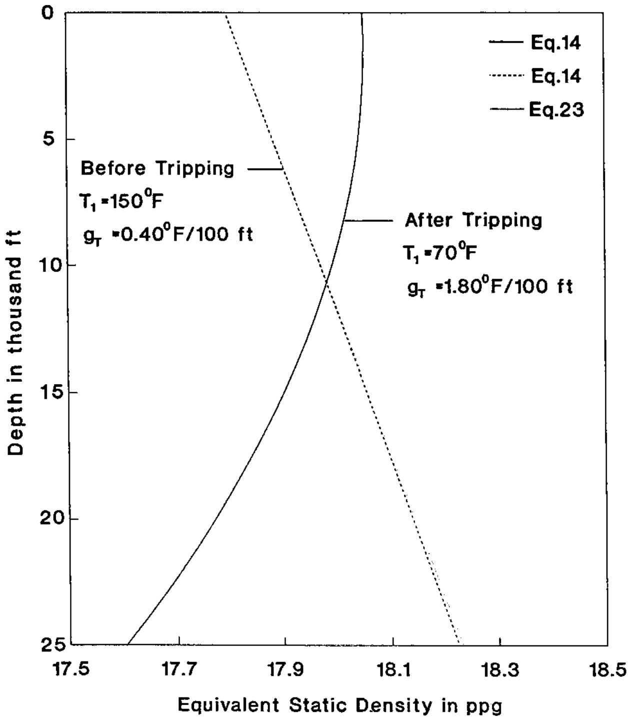

Fig. 5—Variations in equivalent static density during tripping with 18-lbm/gal water-based mud (Mud 3).

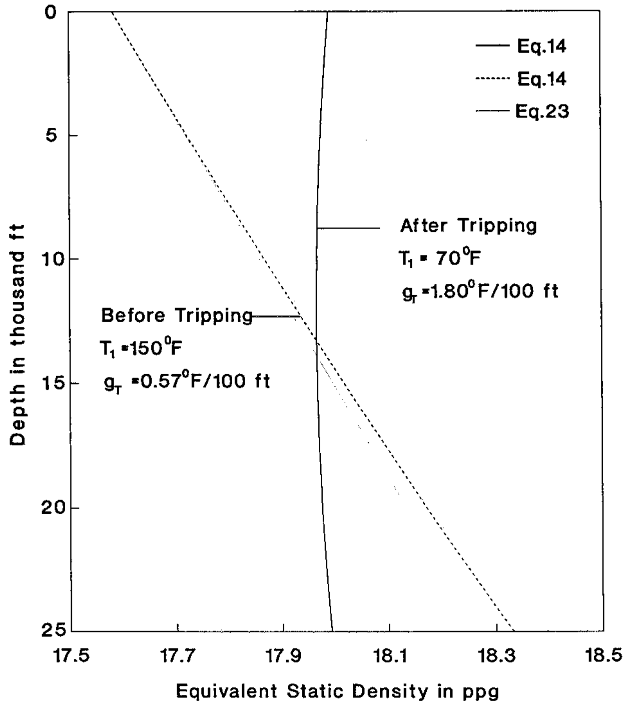

Fig. 6—Variations in equivalent static density during tripping with 18-lbm/gal diesel-oil-based mud (Mud 6).

Case 2

p-ρ-T relationship for water-based muds is established to be

$$\rho_m = \rho_{m0}\exp[\alpha(p - p_0) - \beta(T - T_0) - \gamma(T - T_0)^2]. \quad (19)$$

$F(D)$ for the case of water-based muds is given by

$$F(D) = \frac{0.052a\rho_{m0}\exp(a^2)}{\sqrt{\gamma}\, g_T}\frac{\sqrt{\pi}}{2}[erf(D_{D2}) - erf(a)]. \quad (20)$$

From the definition, the error function $erf(D_{D2})$ can be written as

$$erf(D_{D2}) = \frac{2}{\sqrt{\pi}}\int_0^{D_{D1}} \exp(-u^2)du, \quad (21)$$

and the dimensionless depth variable D_{D2} is given by

$$D_{D2} = \sqrt{\gamma}\, g_T D + a. \quad (22)$$

Approximate Solution for Cold Wells

When g_T is low, which is the case with the cold wells, the contribution from higher order terms in the right hand side of Eq. 14 to ESD is not so significant. For such cases, an approximate and simple equation can be derived for ESD. After substituting either Eq. 16 or Eq. 20 with series representation for error functions in Eq. 14 and expanding the natural logarithm in terms of a series and neglecting the D^3 and higher degree terms, one can get

$$ESD \approx \rho_{m0}\left[1 + \frac{1}{2}(0.052\rho_{m0}\alpha - \beta g_T)D\right]. \quad (23)$$

Corrections for Other Surface Conditions

In the present analysis, it is assumed that at surface pressure (p_0) and temperature (T_0) are 14.7 psia and 59°F, respectively. On occasions, when the surface conditions are p_1 and T_1, which are other than p_0 and T_0, the above analysis can be used with appropriate corrections on ρ_{m0} and β. Defining ρ_{m1} and β_1 as

$$\rho_{m1} = \rho_{m0}\exp[\alpha(p_1 - p_0) - \beta(T_1 - T_0) \pm \gamma(T_1 - T_0)^2], \quad (24)$$

$$\beta_1 = \beta \mp 2\gamma(T_1 - T_0). \quad (25)$$

If the surface pressure and temperature are p_1 and T_1 respectively, then ρ_{m1}, β_1, p_1, and T_1 should be used in place of ρ_{m0}, β, p_0, and T_0 respectively in Eqs. 9, 13, 14, 16 through 18, and 20 through 23.

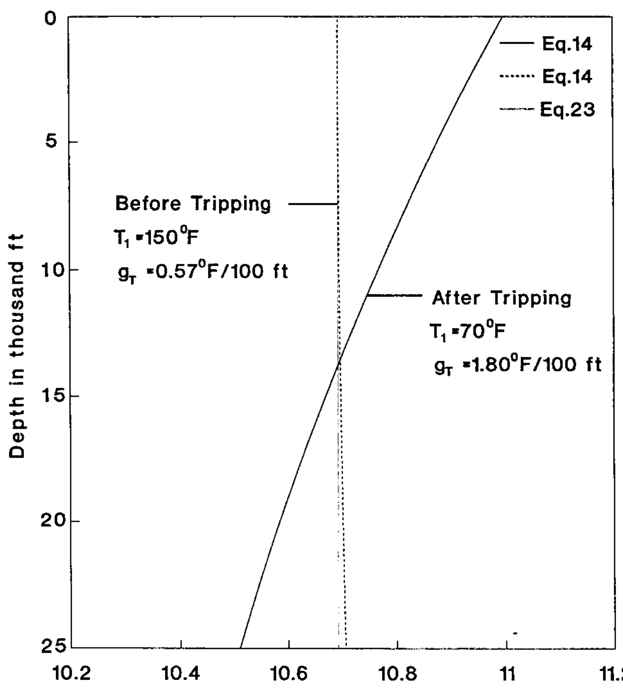

Fig. 7—Variations in equivalent static density during tripping with 11-lbm/gal diesel-oil-based mud (Mud 7).

TABLE 3—COMPARISON OF EQUIVALENT STATIC DENSITIES AT THE SURFACE AND AT THE BOTTOM OF THE EXAMPLE WELL WITH DIFFERENT MUDS DURING TRIPPING

	Equivalent Static Density (*ESD*) in lbm/gal					
	Before Tripping (T_1=150°F)			After Tripping T_1=70°F, g_T=1.8°F/100 ft		
		Bottom			Bottom	Reduction at
Mud No.	Surface	Eq.14	Eq.23	Surface	Eq.14	Bottom
1	10.505	10.571	10.584	10.742	10.118	0.453
2	13.407	13.610	13.592	13.656	13.012	0.598
3	17.796	18.225	18.232	18.051	17.604	0.621
4	10.606	10.791	10.773	10.968	10.516	0.275
5	13.882	14.332	14.305	14.257	13.994	0.338
6	17.581	18.333	18.273	17.990	17.992	0.341
7	10.695	10.706	10.692	10.998	10.509	0.197
8	16.652	16.881	16.863	16.982	16.642	0.239
9	10.691	10.741	10.731	10.986	10.523	0.218
10	16.650	16.882	16.873	16.982	16.588	0.294
11	10.674	10.725	10.711	10.987	10.514	0.211
12	16.637	16.894	16.876	16.983	16.626	0.268

Before Tripping, for Muds 1 through 3, g_T=0.40°F/100 ft and for Muds 4 through 12 g_T=0.57°F/100 ft.

Static Pressure Variations During Tripping

Because a large number of reported blowouts occurred during tripping, an attempt is made in this section to estimate the static pressure variations during tripping with the help of Eq. 14. Before tripping, the well is usually under continuous circulation for several hours. Raymond[10] analyzed the temperature distributions in circulating drilling fluids. His analysis showed that with normal circulating rates, once a few hole volumes of mud were circulated out, the well attains a psuedosteady state thermal equilibrium in which the temperatures in the bottom half of the well are significantly lower than that of the geothermal, while the upper half becomes warmer. With these conditions, the well is expected to have low temperature gradient. When the circulation is stopped before tripping, the temperature gradient in the well steadily increases toward the geothermal level. For the long tripping times usually observed in deep wells, the final temperature gradient before restarting the circulation can be very close to the geothermal gradient. To estimate the variations in static pressures during tripping, an example well with a depth of 25,000 ft is chosen. The borehole diameter, circulation rate, and geothermal gradient are assumed to be 8½ in., 300 gal/min, and 1.8°F/100 ft, respectively. Under these conditions, with the outlet mud temperature of 150°F, approximate thermal gradients before tripping are estimated from Raymond's analysis as 0.4 and 0.57°F/100 ft for water- and oil-based muds respectively. After the trip, the thermal gradient and the surface temperature are assumed to be 1.8°F/100 ft and 70°F, respectively. In both cases, the pressure of mud at surface is assumed to be 14.7 psia. Equivalent static density profiles for these two thermal regimes are computed from Eq. 14 using the constants given in Table 2 and the corrections given by Eqs. 24 and 25 and are plotted in **Figs. 5 through 7** for Muds 3, 6, and 7, respectively. Eq. 23 is also plotted in the same figures as the dotted line for the thermal regimes existing before tripping that are characterized by low thermal gradients. In **Table 3,** ESD values predicted by Eq. 14, at the surface and at the bottom of the example well for the two thermal regimes, are given for all twelve muds. Also given in Table 3 are ESD values at the bottom of the well predicted by Eq. 23 for the before-tripping case and the reduction in ESD at the bottom of the well during tripping, as predicted by Eq. 14.

Results and Discussion

From Table 1 and from Figs. 1 through 3, it is observed that the empirical model fits the measured data of McMordie *et al.*[1] for Muds 1 through 6 better than the Sorelle *et al.*'s model and the compositional model. For the measured data of two diesel-oil muds of Peters *et al.*[2] (i.e., Muds 7 and 8), the empirical model is observed to fit better than that of Sorelle *et al.*[6] For these two cases, average errors in empirical and compositional models are observed to be identical. For the muds prepared from two mineral oils A and B, the compositional model appears to be marginally better than the empirical model. It can be concluded that the empirical model represents the p-ρ-T behavior more accurately than the other models for the majority of the muds for which measured data are available.

From Figs. 2 and 3, it is seen that for the diesel-oil-based muds, Sorelle *et al.*'s model fits measured data of Mud 7 better than that in the case of Mud 4 in the high-pressure, low-temperature region. Similar observations are also made while comparing the data for Mud 8 and Muds 5 and 6. Therefore, the diesel oil whose p-ρ-T data were used to develop Eq. 3 appears to be closer to the diesel oil used in the preparation of Muds 7 and 8. In the high-temperature, low-pressure region, the predicted values of Sorelle *et al.*'s model deviate significantly from the measured data for Muds 4 through 6 and to a less extent for Muds 7 and 8. This may be caused by the nature of p-ρ-T behavior of hydrocarbon liquids, which deviates significantly from the type of linear relationship assumed in Eq. 3 in this region. It is observed from Fig. 4 that the two 11-lbm/gal diesel-oil-based muds are having different temperature profiles. It is of interest that the compositions of the two 11-lbm/gal diesel-oil-based muds differ marginally. Estimated values of empirical constant α, which is an indirect measure of compressibility of the mud, appear to differ by an order of magnitude in these cases, which suggests that the two diesel oils used in the preparation of the Muds 4 through 8 are not similar with respect to their compressibility and thermal expansion characteristics even though they are grouped under the same broad category of diesel oil No. 2. However, the empirical model indicates the least deviation in all these cases.

Kutasov[9] observed that at higher temperatures, physicochemical interactions between the solids and liquid might influence p-ρ-T behavior of muds. Further, the types and quantities of additives used for the preparation of the mud vary widely from location to location. Elsen *et al.*[11] discussed the successful application of 18-lbm/gal lime-based water mud in a HPHT deep well. They reported the use of six other special additives. Often, it becomes impractical to associate the mud in the borehole with any specific composition,[11] as several additives are added at different times to adjust the mud parameters, such as the density, rheology, shale inhibition characteristics, etc., to suit a specific drilling situation. In these circumstances, it is always advisable to collect several sets of p-ρ-T data on a sample of mud from the borehole for the accurate estimation of p-ρ-T effects on the static pressures.

From Figs. 5 through 7, it is observed that during tripping ESD increases in the upper sections of the example well and decreases in the lower sections. The extent of decrease at the bottom of the well is different for different muds. There exists an intermediate depth where the ESD remains unchanged at the end of the trip. In general, water-based muds exhibited higher reductions in ESD while the two oil-based muds prepared from diesel oil No. 2 (Muds 7 and 8) exhibited lower reductions when compared to the other muds of identical initial mud weights. A maximum reduction in ESD of about 0.62 lbm/gal or a loss of static pressure of about 800 psi occurs in the case of 18-lbm/gal water-based mud (Fig. 5). This is a significant variation. Its magnitude and direction are similar to that of swab pressure. If it is not recognized and mud weight is not compensated adequately before tripping, it can lead to underbalance conditions. A minimum reduction of about 0.2 lbm/gal in ESD occurs in the case of Mud 7 (Fig. 7). From Table 3, it is observed for Mud 4, which is a diesel oil No. 2-based mud, the reduction in ESD is 0.27 lbm/gal, which is higher than that for Mud 7. As discussed in the previous paragraph, though these muds are nearly identical in their compositions, they exhibit different compressibility and thermal expansion characteristics that are reflected on the static pressures exerted by them. It is observed from Table 3 that the predicted values of ESD from Eq. 23 are very close to that predicted by Eq. 14 for before-tripping case. For these twelve cases, at depth of 25,000 ft, the average error between the approximated values obtained from Eq. 23 and the actual values given by Eq. 14 is estimated to be about 0.13%. Therefore, it can be concluded that Eq. 14 represents ESD profiles fairly accurately for cold wells.

For Mud 6 (Fig. 6), ESD values at the top and bottom of the well are estimated to be equal in the thermal regime that exists after tripping. For this case, the linear gradient estimated from Eq. 9 is 1.64°F/100 ft, which is comparable with the assumed value of 1.8°F/100 ft. From Fig. 7, it may be observed that before tripping, ESD values at the surface and at the bottom of the example well are 10.69 and 10.71 respectively, which suggest that the mud weights remain nearly constant at all depths in the well. Thermal gradients computed by linear approximation of Eq. 9 is 0.56°F/100 ft, which is nearly equal to the assumed gradient of 0.57°F/100 ft.

Reduction in static pressure during tripping indicates that the quantity of mud in the borehole is decreasing. During this phase, if the pipe is left undisturbed, the well expels a certain volume of mud that will appear to be a pit gain. After the gain, if the circulation is resumed at the same rate, then equal volume of mud is accommodated back in the hole gradually, which will appear to be a partial mud loss. For the above example well, these volumes are estimated to be a few tens of barrels. If the well is shut in on gain, a pressure buildup will be observed at the wellhead that is approximately equal to the decrease in static pressure at the bottom in open condition. Details of estimation of maximum gain, surface shut-in pressure, and the rate at which they occur are given elsewhere.[12]

Recommendation

The types and quantities of additives used in the preparation of mud vary widely at different locations and sometimes at different stages of the same well. Often, it becomes impractical to keep track of the actual composition of the mud in the well as several additives are added at different times to maintain desired mud parameters to suit a specific drilling situation. In such circumstances, it is recommended that several sets of p-ρ-T data should be obtained on a sample of mud from the well and the empirical constants of Eq. 6 should be estimated such that the above analysis can be used with more confidence in a given drilling situation.

Conclusions

1. The empirical model given by Eq. 6 represents the p-ρ-T behavior of a majority of the muds for which the measured data are available more accurately than the other models.
2. A priori prediction of whether mud weight increases or decreases with depth can be made with Eq. 9, which is the temperature profile in the well that has constant mud weight at all depths.
3. Different oils available under the category of diesel oil No. 2 that were used in the preparation of oil-based muds can exhibit different compressibility and thermal expansion characteristics, which are reflected in the p-ρ-T behavior of the muds prepared with them.
4. Static pressure variations can be estimated accurately using Eq. 13. ESD parameter as defined by Eq. 14, which incorporates the mud p-ρ-T behavior, pressure and temperature of mud at the surface, thermal gradient, and depth of the well, can be used in place of normally used mud weight term to have a better understanding of several critical drilling situations.
5. Simple relationship given by Eq. 23 predicts ESD profiles in cold wells fairly accurately.
6. During high-temperature deep well drilling, a reduction in ESD occurs at the bottom of the well during tripping. The extent of reduction depends on the type of mud in the well. In some cases, the reduction is significant enough and may require appropriate corrective measures before tripping.

Acknowledgments

I thank the management of Oil India Ltd. for permitting this work to be published. Thanks to B.C. Bora, chairman and managing director of Oil and Natural Gas Corp. Ltd., for his continued support and encouragement during the course of this work.

Nomenclature

a = dimensionless constant defined in Eq. 17
D = depth, L, ft
D_{D1}, D_{D2} = dimensionless depth defined in Eqs. 18 and 22
erf = error function defined in Eq. 21
ESD = equivalent static density defined by Eq. 14
$F(D)$ = functions defined in Eqs. 16 and 20
g_T = thermal gradient, T/L, °F/100 ft
k = integer variable
N = number of data points
p = pressure, m/Lt^2, psia
T = temperature, T, °F
u = dummy variable
V_f = fractional volume of liquid phase
α = empirical constant, psi^{-1}
β = empirical constant, °F^{-1}
γ = empirical constant, °F^{-2}
ρ = density, m/L^3, lbm/gal

Subscripts

h = hydrocarbon
m = mud
se = static, equivalent
w = water
0 = at standard conditions
1 = at any pressure p_1 and temperature T_1

References

1. McMordie Jr., W.C., Bland, R.G. and Hauser, J.M.: "Effect of Temperature and Pressure on the Density of Drilling Fluids," paper SPE 11114 presented at 1982 SPE Annual Technical Conference and Exhibition, New Orleans, Sept. 26–29.

2. Peters, E.J., Chenevert, M.E. and Zhang, C: "A Model for Predicting the Density of Oil-Based Muds at High Pressures and Temperatures," *SPEDE* (June 1990) 141-48; *Trans.*, AIME, 289.
3. Mathiesen, R.: "Surveys Define Norwegian HP/HT Well Problems," *Ocean Industry* (July 1992) 45–47, 58.
4. Hoberock, L.L., Thomas, D.C. and Nickens H.V.: "Bottom-Hole Mud Pressure Variations due to Compressibility and Temperature Effects," paper presented at the 1982 IADC Drilling Technology Conference, Houston, March 9–11.
5. Peters, E.J., Chenevert, M.E. and Alhamadah, A.M.: "OILMUD: A Microcomputer Program for Predicting Oil-Based Mud Densities and Static Pressures," *SPEDE* (March 1991) 57–59.
6. Sorelle, R.R. *et al.*: "Mathematical Field Model Predicts Downhole Density Changes in Static Drilling Fluids," paper SPE 11118 presented at the 1982 SPE Annual Technical Conference and Exhibition, New Orleans, Sept. 26–29.
7. Kutasov, I.M.: "Water FV Factors at Higher Pressures and Temperatures," *Oil & Gas J.* (Mar. 20, 1989) 102–104.
8. Babu, D.R.: "Equation Corrects Kill-water Density Value in Deep, Hot Wells," *Oil & Gas J.* (Aug. 2, 1993) 74–75.
9. Kutasov, I.M.: "Empirical Correlation Determines Downhole Mud Density," *Oil & Gas J.* (Dec. 22, 1988) 61–63.
10. Raymond, L.R.: "Temperature Distribution in a Circulating Drilling Fluid," *JPT* (1969) 333–341.
11. Elsen, J.M. *et al.*: "Application of a Lime-Based Drilling Fluid in a High-Temperature/High-Pressure Environment," *SPEDE* (March 1991) 51–56.
12. Babu, D.R.: "Effect of p-ρ-T Behavior of Muds on Loss/Gain During High-temperature Deep Well Drilling," accepted for publication in *J. Pet. Sci. Eng.*

SI Metric Conversion Factors

bbl	× 1.589 873	E−01	= m^3
ft	× 3.048*	E−01	= m
°F	(°F−32)/1.8		= °C
gal	× 3.785 412	E−03	= m^3
in.	× 2.54*	E+00	= cm
lbm	× 4.535 924	E−01	= kg
psi	× 6.894 757	E+00	= kPa

*Conversion factor is exact.

SPEDC

D. Ram Babu is an assistant general manager in the R&D division of Engineers India Ltd., New Delhi. Apart from drilling and production problems, his current research interests include design and development of reactors for refinery applications. His two decades of research experience includes the areas of Athabasca bitumen recovery, chemical flooding, formation water treatment, paraffin problems, sand control, and two-phase flow in field pipelines. He held postdoctoral positions at U. of Toronto and U. of Ottawa, and he was a visiting scientist at Schlumberger Cambridge Research. Babu holds a BTech degree from Regional Engineering C., Warangal, and a PhD degree from Indian Inst. of Science, Bangalore, both in chemical engineering. Babu's e-mail address is drb@eilrnd.ernet.in.