AADE-03-NTCE-60

Pressure Requirements in Foam Drilling

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This paper was prepared for presentation at the AADE 2003 National Technology Conference "Practical Solutions for Drilling Challenges", held at the Radisson Astrodome Houston, Texas, April 1 - 3, 2003 in Houston, Texas. This conference was hosted by the Houston Chapter of the American Association of Drilling Engineers. The information presented in this paper does not reflect any position, claim or endorsement made or implied by the American Association of Drilling Engineers, their officers or members. Questions concerning the content of this paper should be directed to the individuals listed as author/s of this work.

Abstract

Theoretical analyses with Guo *et al.*'s foam hydraulics model shows that injection GLR is a dominating factor affecting ECD, EMW and the maximum depth in stable foam drilling. The ECD, EMW, minimum backpressure and depth limit curves for stable foam drilling with a wide range of GLR (1 to 20) are generated in this study for field applications.

Introduction

Foam stability should be taken good consideration during foam drilling. The in-situ pressures must be controlled to maintain the right gas fraction in the range of stable foam. Accurate prediction of shut-in and flowing bottom hole pressures is particularly important for foam drilling.

A number of rheology models have been developed for foam hydraulics calculations in the past three decades. These models include Beyer *et al.,*[1] Blauer *et al.*,[2] Sanghani,[3] Reidenbach *et al.*,[4] Valko-Economides,[5] and Gardiner *et al.*[6] Ozbayoglu *et al.*[7] conducted a rheological study for foam based on measurements from a 90 ft long horizontal pipe model. Based on their experimental data they concluded that there is no "best" model for predicting the pressure losses during foam flow in pipes under the experimental conditions. Models that may predict pressure losses closer to actual values in one case may not be suitable for another condition. Griffin *et al.*[8] and Nakagawa *et al.*[9] also indicate this confliction.

There are also discrepancies among hydraulics models for stable foam. Guo *et al.*[10] presented a trial and error method to couple the frictional and hydrostatic pressure components through the pressure-dependent fluid density. Their technique gives results similar to that given by the computer models of Anderson[11] and Okpobiri and Ikoku.[12] Guo and Ghalambor[13] formulated a general governming equation coupling the frictional and hydrostatic pressure components in vertical and inclined boreholes for aerated fluid hydraulics. Recently, Guo *et al.*[14,15] developed and validated a closed form analytical solution to the Guo-Ghalambor.[13]

In this study, Guo *et al.'s*[14,15] hydraulics model was used in foam stability control analysis. Theoretical analyses with the model shows that injection GLR is a dominating factor affecting ECD, EMW and the maximum depth in stable foam drilling. The ECD, EMW, minimum backpressure and depth limit curves for stable foam drilling with a wide range of GLR (1 to 20) are generated in this study for field applications.

Mathematical Model

Assumptions. The mathematical model was derived by Guo *et al.'s*[14,15] based on the following assumptions:

1) Lamilar flow exists in the annular space
2) Power Law model applies to foam
3) Slippage effect between phases is negnegible.

Solution. The procedure of obtaining the closed form model solution was presented by Guo *et al.*[16].

$$b(P-P_s)+\frac{1-2bM}{2}\ln\left|\frac{(P+M)^2+N}{(P_s+M)^2+N}\right|$$
$$-\frac{M+bN-bM^2}{\sqrt{N}}\left[\tan^{-1}\left(\frac{P+M}{\sqrt{N}}\right)-\tan^{-1}\left(\frac{P_s+M}{\sqrt{N}}\right)\right]$$
$$=a(1+d^2e)L \quad (1)$$

where

$$a=\frac{53.3b\gamma_l T+S_g}{53.3T}\cos(\theta) \quad (2)$$

$$b=\frac{1-\Gamma_s}{P_s\Gamma_s} \quad (3)$$

$$c=\frac{144P_sT}{60AT_s} \quad (4)$$

$$d=\frac{144}{60A}\left(\frac{Q_l}{7.48}+\frac{5.615Q_{fx}}{60}\right) \quad (5)$$

$$e=\frac{f}{2gD_H\cos(\theta)} \quad (6)$$

$$M = \frac{cde}{1 + d^2 e} \tag{7}$$

$$N = \frac{c^2 e}{\left(1 + d^2 e\right)^2} \tag{8}$$

and

P = pressure, lb/ft^2
L = borehole length (measured depth), ft
g = 32.2ft/sec^2
S_g = gas specific gravity
P_s = surface back pressure, lb/ft^2
θ = inclination angle, degree
γ_l = the average specific weight of liquid phase, lb/ft^2
Γ_s = foam quality at choke, fraction
T = temperature, ^{o}R
T_s = temperature at choke, ^{o}R
A = cross-sectional area of flow path, in^2
Q_l = liquid injection rate, gal/min
Q_{fx} = formation influx rate, bbl/hour
D_H = hydraulic diameter of the flow path, ft
f = Moody friction factor

With a given depth L and surface choke pressure, the wellbore pressure P can be solved by equation (1) using numerical aloborithm such as Newton-Raphson iteration method. The easiest way to solve this equation is to use the Goal Seek function built in the MS Excel spreadsheet.

Friction Factor Calculation
Ozbayoglu *et al.*[7] conducted a rheological study for foam based on measurements from a 90 ft long horizontal pipe model. Their experimental data indicate that foam rheology can be better characterized by the Power Law Model for 0.70 and 0.80 foam qualities, by Bingham plastic model for 0.90 foam quality. On the basis of this research, we choose the Power Law model to estimate the friction factor *f.* The stable foam falls into laminar flow regime under foaming drilling conditions. It can be expressed as:

$$f = \frac{64}{\text{Re}} \tag{9}$$

The Reynold's number for foam is expressed as:

$$\text{Re} = \frac{\gamma_{fa} D_H v_f}{\mu_e} \tag{10}$$

where,

γ_{fa} = the average foam density, lb/ft^3
v_f = foam velocity, fps
μ_e = effective foam viscosity, lb/ft-s

The effective foam viscosity for an average foam quality can be estimated based on consistency index *K* and flow behaviour index *n*:

$$\mu_e = K\left(\frac{2n+1}{3n}\right)^n \left(\frac{12 v_f}{D_H}\right)^{n-1} \tag{11}$$

Sanghani's work,[3] provide *K* and *n* at different values of foam quality index Γ. Guo *et al.*[15] fitted their data and obtained the following correlations:

$$\begin{aligned} K = &-0.15626 + 56.147\Gamma - 312.77\Gamma^2 + 576.65\Gamma^3 \\ &+ 63.960\Gamma^4 - 960.46\Gamma^5 - 154.68\Gamma^6 \\ &+ 1670.2\Gamma^7 - 937.88\Gamma^8 \end{aligned} \tag{12}$$

and

$$\begin{aligned} n = &\,0.095932 + 2.3654\Gamma - 10.467\Gamma^2 + 12.955\Gamma^3 \\ &+ 14.467\Gamma^4 - 39.673\Gamma^5 + 20.625\Gamma^6 \end{aligned} \tag{13}$$

Model Applications
Foam Stability Control. Foam quality should be controlled between 0.55 and 0.97 to keep foam stable during drilling. Based on the difinition of foam quality and ideal gas law, the foam quality can be expressed as:

$$\Gamma = \frac{\dfrac{4.07 Q_{go} T}{P}}{\dfrac{4.07 Q_{go} T}{P} + 0.13369 Q_l + 0.09358 Q_{fx}} \tag{14}$$

where,

Γ = foam quality at the point of interest
T = temperature at the point of interest, ^{o}R
Q_{fx} = formation fluid influx rate, bbl/hour
Q_l = liquid injection rate, gpm
Q_{go} = gas flow rate at standard condition, scfm

Equation (14) can be express as function of *GLR:*

$$\Gamma = \frac{\dfrac{4.07 GLR \cdot T}{P}}{\dfrac{4.07 GLR \cdot T}{P} + 0.09358 \dfrac{Q_{fx}}{Q_l} + 0.13369} \tag{15}$$

where,

$GLR = \dfrac{Q_{go}}{Q_l}$, scfm/gpm

The gas phase volume is compressed as pressure increases. Therefore, the maximum *GLR* without backpressure applied will be at the surface condition when:

T=520°R, P=2116lb/ft^2

The equation (15) yields:

$$GLR_{\max} = \frac{\Gamma_{\max}}{1-\Gamma_{\max}}\left(0.13369 + 0.09358\frac{Q_{fx}}{Q_l}\right) \quad (16)$$

Γ_{max} -- the maximum allowable stable foam quality without backpressure applied

For example, If the formation fluid influx rate Q_{fx} is zero, Eq. (16) yields GLR_{max} = 4.32 scfm per gpm with $\Gamma\max = 0.97$. For a liquid injection rate of 100 gpm, this means the maximum allowable gas injection rate without requiring backpressure is 432 scfm. When injection *GLR* is higher than the GLR_{max}, the backpressure is required to keep foam stable. Figure 1 presents a quick solution chart for determining the GLR_{max} for different Γ_{max} at different formation fluid influx ratios. This figure shows that the GLR_{max} increases with Γ_{max}, and the formation fluid influx enhances GLR_{max} without requiring backpressure.

From equation (15), by setting $\Gamma=\Gamma_{max}$, $P=P_{s-min}$, *and* $T=T_s$, the minimum required backpressure can be solved as:

$$P_{s-\min} = \frac{2116(1-\Gamma_{\max})GLR}{\Gamma_{\max}\left(0.13369 + 0.09358\frac{Q_{fx}}{Q_l}\right)} \quad (17)$$

Equation (17) can be used in foam stability control. When injection *GLR* is higher than GLR_{max}, the foam will be unstable in the borehole, if no backpressure applied. The minimum required backpressure to control foam stability can be solved by equation (17). Figure 2 presents a quick solution chart for determining the minimum required backpressure for foam quality (Γ_{max}=0.97) at various GLR and different formation fluid influx ratios. This figure shows that the minimum required backpressure increases with injection GLR, and as the formation fluid influx decreases, the required minimum backpressure decreases.

Foam also becomes unstable when the pressure is significantly high. From equation (15), as $\Gamma=\Gamma_{min}$, the maximum pressure at which the foam is stable can be calculated by:

$$P_{\max} = \frac{4.07\cdot T(1-\Gamma_{\min})\cdot GLR}{0.13369\Gamma_{\min} + 0.09358\frac{Q_{fx}}{Q_l}\Gamma_{\min}} \quad (18)$$

Figure 3 presents a quick solution chart for determining the maximum pressure at various GLR and different foamation fluid influx ratios. This figure shows that the maximum allowable pressure increases with injection GLR, and decreases with the formation fluid influx.

Using P_{max} and $P_{s-min,}$ in Eq. (1). The maximum depth for stable foam drilling can be solved by:

$$b(P_{\max} - P_{s-\min}) + \frac{1-2bM}{2}\ln\left|\frac{(P_{\max}+M)^2+N}{(P_{s-\min}+M)^2+N}\right| - \frac{M+bN-bM^2}{\sqrt{N}}\left[\tan^{-1}\left(\frac{P_{\max}+M}{\sqrt{N}}\right) - \tan^{-1}\left(\frac{P_{s-\min}+M}{\sqrt{N}}\right)\right] = a(1+d^2e)L_{\max} \quad (19)$$

Equation (20) can be solved using the Goal Seek function built in the MS Excel spreadsheet. Figures 4 to 9 present depth limit charts computed from Eq. (20) with two liquid flow rates and Γ_{min}=0.55 for three annulus sizes. The liquid injection rates are keeped constant in the figures. The gas injection rates are changed with the same GLR scale. Compare Figs. 4 and 5, Figs. 6 and 7, and Figs. 8 and 9, we can find that for the same annulus hole, although the liquid injection rates are different, same GLR will predict the almost same depth limits for the stable foam drilling. Therefore, GLR is the key factor affecting depth limit in stable foam drilling.

The GLR_{max}, P_{max}, P_{s-min} and L_{max} give us the range of the pressure and depth for stable foam drilling. The Eqs. (16) to (19) can help us to achieve stable foam control during foam drilling.

ECD and EMW Calculation. Accurately prediction of the Equivalent Circulating Density (ECD) and Equivalent Mud Weight is important in drilling. The term ECD is defined as:

$$ECD = \frac{p_{flow} - 14.696}{0.052H} \quad (21)$$

where p_{flow} = flowing pressure, psia

H = $L\cos(\theta)$ = vertical depth, ft

ECD = equivalent circulating density, ppg.

The term EMW is defined as:

$$EMW = \frac{p_{static} - 14.696}{0.052H}$$

where p_{static} = "static" pressure, psia

H = $L\cos(\theta)$ = vertical depth, ft

EMW = equivalent mud weight, ppg.

The flowing pressure at a given depth L can be predicted with Eq. (1) numerically. The "static" pressure at a given depth L can also predicted with Eq. (1) numerically when setting friction factor very small close to zero. The Goal-Seek function built in the MS Excel spreadsheet was used as a tool for solving the flowing pressure and "static" pressure in this study.

Predicted ECD's for three annulus sizes are also presented in Figs. 4 through 9. Comparisons of Figs. 4 and 5, 6 and 7, and 8 and 9 indicate that for the same annulus hole, although the liquid injection rates are different, same GLR will predict almost same ECD at same depth for the stable foam drilling. Therefore, the ECD in foam drilling depends strongly on GLR.

Predicted EMW's for three annulus sizes are also presented in Figs. 10 through 15. Comparisons of Figs. 10 and 11, 12 and 13, and 14 and 15 indicate that for the same annulus hole, although the liquid injection rates are different, same GLR will predict almost same EMW at same depth for the stable foam drilling. Therefore, the EMW in foam drilling depends strongly on GLR.

Conclusions

Guo *et al.*'s mathematical model can be effectively used in ECD, EMW prediction and foam quality control in stable foam drilling. Theoretical analysis with the model show that injection GLR is a dominating factor affecting ECD, EMW and depth limit in stable foam drilling.

Nomenclature

A = flow path cross sectional area, in^2.
D_H = hydraulic diameter of the flow path, ft
ECD = equivalent circulating density, ppg.
EMW = equivalent mud weight, ppg
f = Moody friction factor, dimensionless
g = 32.2 ft/sec^2
L = length (measured depth), ft
H = $L\cos(\theta)$ = vertical depth, ft
P = pressure, lb/ft^2
P_o = surface gas pressure, lb/ft^2
P_s = backpressure at surface choke, lb/ft^2
P_{bh} = bottom hole pressure, lbf/ft^2
$P_{s\text{-}min}$ = minimum required backpressure, lb/ft^2
p_{flow} = flowing pressure, psia
p_{static} = "static" pressure, psia
Q_{fx} = formation fluid influx rate, bbl/hr.
Q_{fh} = foam volumetric rate at the bottom hole,ft^3/sec
Q_{gh} = gas volumetric rate at the bottom hole, ft^3/sec
Q_o = gas flow rate at standard condition, scfm
Q_l = liquid flow rate, gpm
S_g = specific gravity of gas, air = 1.
T = absolute temperature, ^{o}R
T_s = ambient temperature, ^{o}R
v_f = foam velocity, ft/sec
γ_g = specific weight of foam-forming gas, lb/ft^3
γ_l = the specific weight of liquid, phase, lb/ft^3
γ_{fb} = foam density at the bottom hole, lb/ft^3
γ_s = cutting density, lb/ft^3
γ_{gb} = gas phase density at the interest point, lb/ft^3
γ_{fa} = the average foam density, lb/ft^3
Γ = foam quality, fraction
Γ_s = foam quality at choke, fraction
Γ_{bh} = designed foam quality index at bottom hole
θ = inclination angle, degree
D_s = cutting equivalent diameter, ft
d_b = bit diameter, inch
R_p = rate of penetration, ft/hour
C_p = particle concentration in the flow path, volume fraction, ≤ 0.04

Acknowledgments

The author is grateful to the Department of Petroleum Engineering at the University of Louisiana at Lafayette for providing Research Assistantship to financially support this study.

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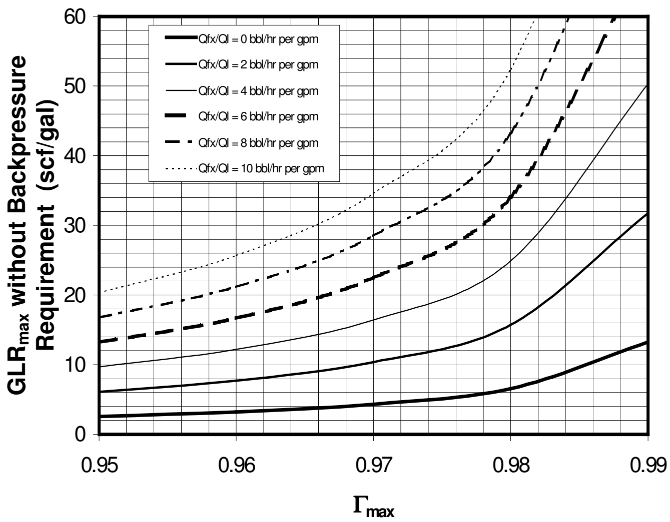

Fig. 1 – The maximum allowable GLR versus Γ_{max} for various formation fluid influx ratios

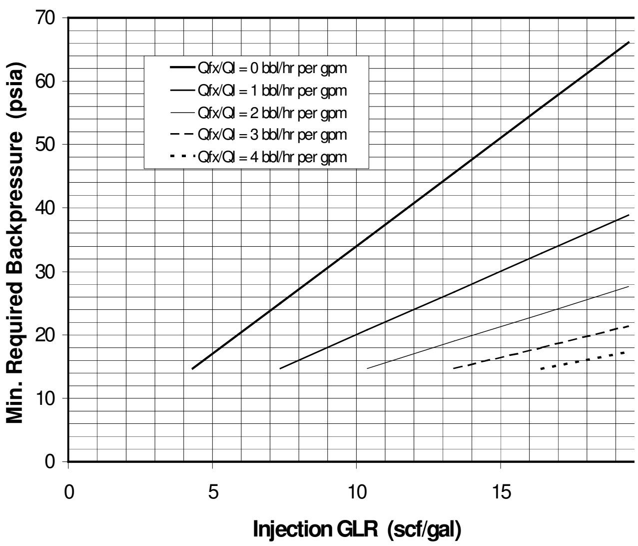

Fig. 2 -- Chart for determining the minimum required backpressure for commonly used foams (Γ_{max} = 0.97) at various GLR and different formation fluid influx ratios.

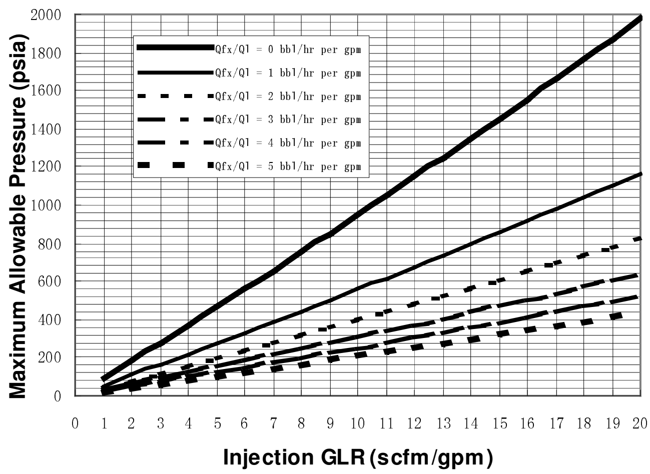

Fig.3- Maximum allowable backpressure for commonly used foams (Γ_{min} =0.55) at different GLR and formation fluid influx ratios.

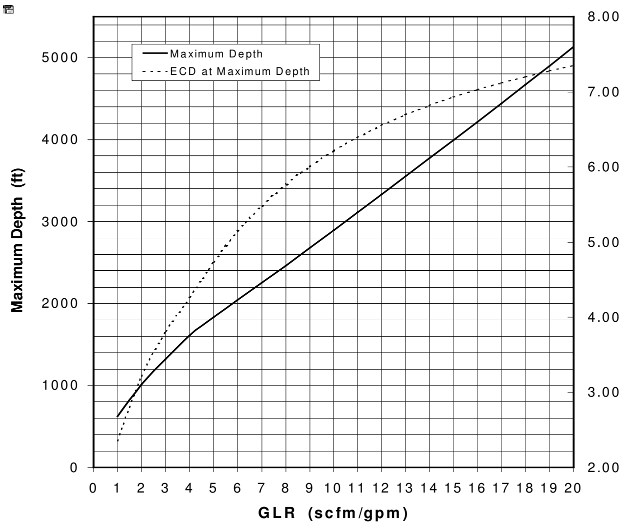

Fig. 4 – Predicted depth limit and ECD with 130 gpm liquid rate and minimum backpressures in a 12.25”x6.325” annulus

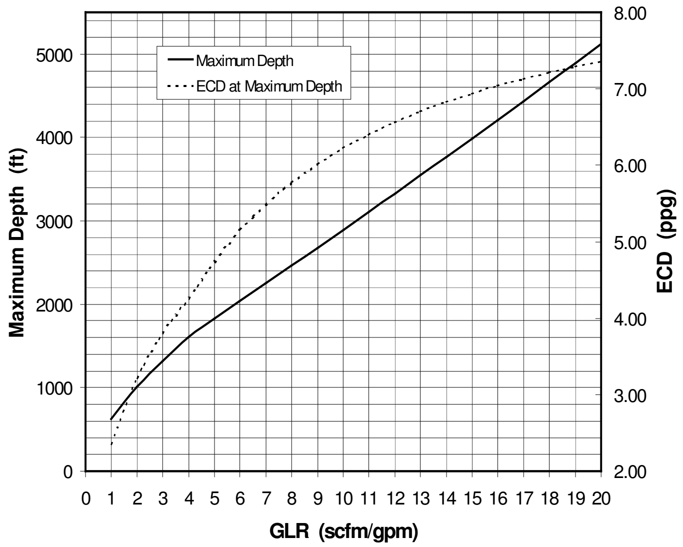

Fig. 5 – Predicted depth limit and ECD with 250 gpm liquid rate and minimum backpressures in a 12.25”x6.325” annulus

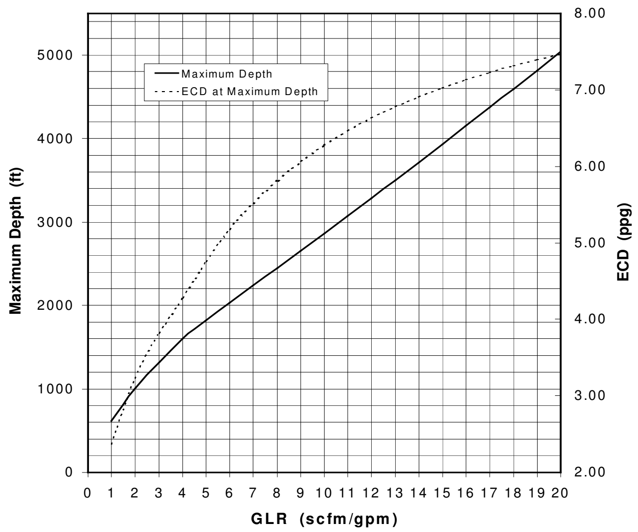

Fig. 7 – Predicted depth limit and ECD with 250 gpm liquid rate and minimum backpressures in a 7.875”x4.5” annulus

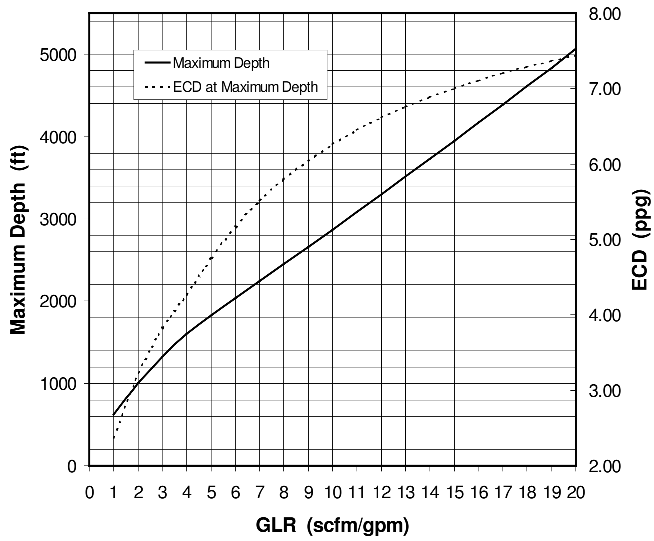

Fig. 6 – Predicted depth limit and ECD with 130 gpm liquid rate and minimum backpressures in a 7.875”x4.5” annulus

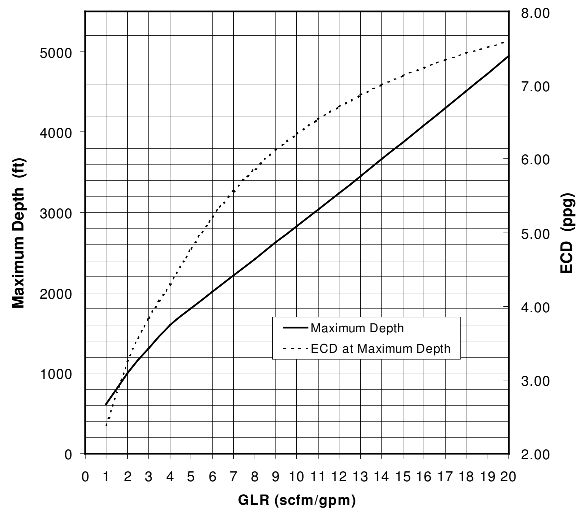

Fig. 8 – Predicted depth limit and ECD with 130 gpm liquid rate and minimum backpressures in a 4.75”x2.375” annulus

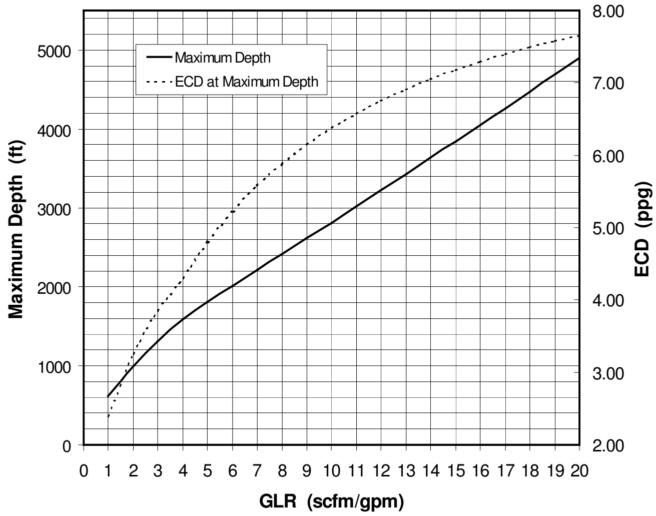

Fig. 9 – Predicted depth limit and ECD with 250 gpm liquid rate and minimum backpressures in a 4.75”x2.375” annulus

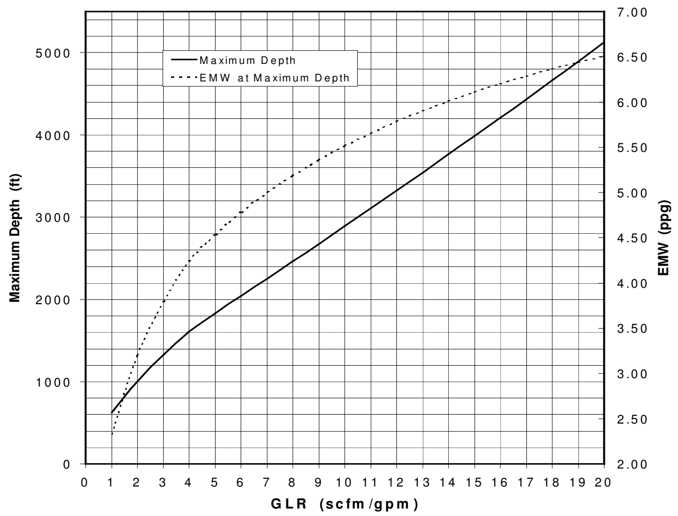

Fig. 11 – Predicted depth limit and EMW with 250 gpm liquid rate and minimum backpressures in a 12.25”x6.325” annulus

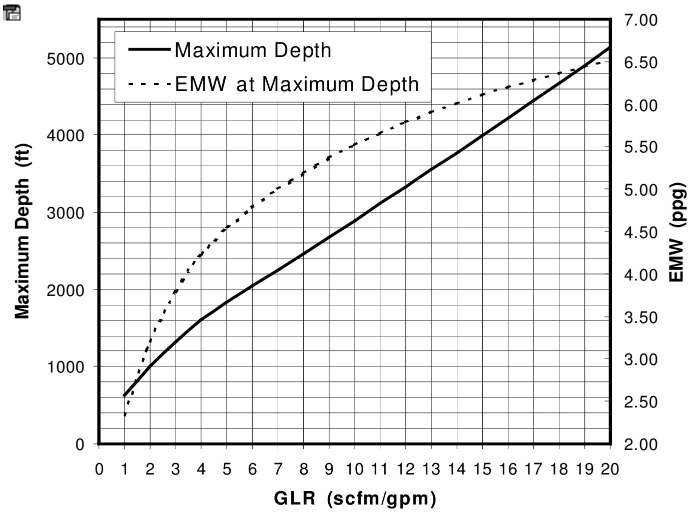

Fig. 10 – Predicted depth limit and EMW with 130 gpm liquid rate and minimum backpressures in a 12.25”x6.325” annulus

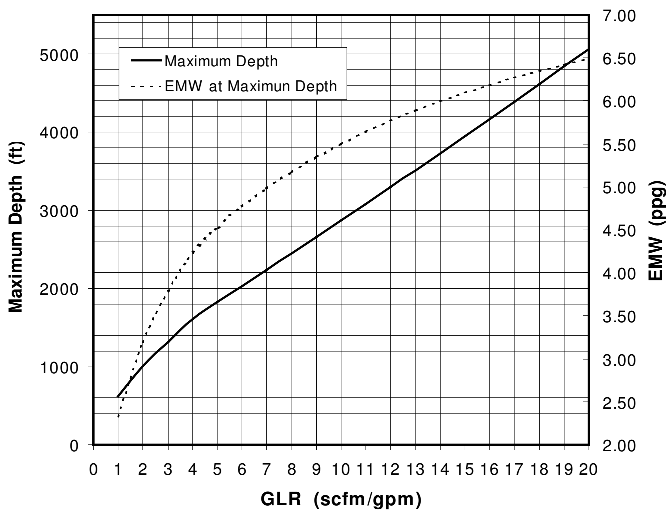

Fig. 12 – Predicted depth limit and EMW with 1**3**0 gpm liquid rate and minimum backpressures in a 7.875”x4.5” annulus

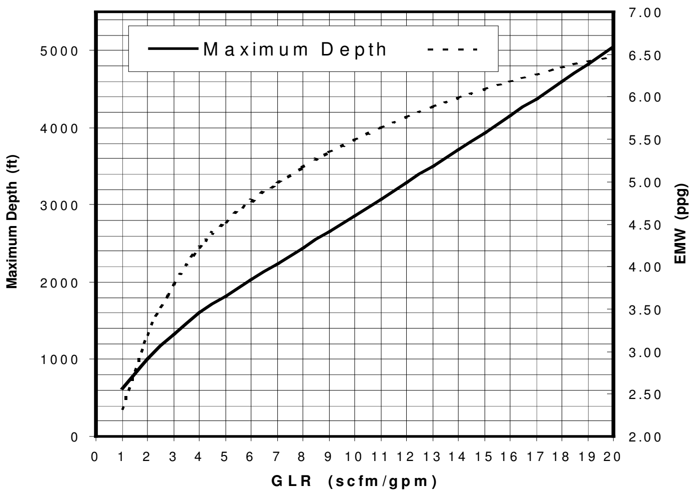

Fig. 13 – Predicted depth limit and EMW with 250 gpm liquid rate and minimum backpressures in a 7.875”x4.5” annulus

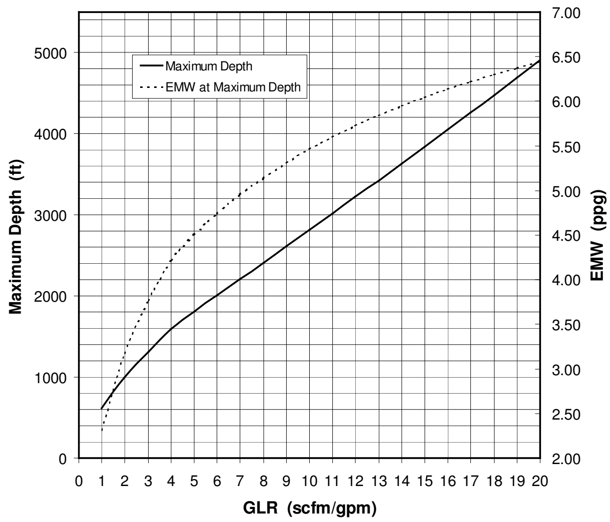

Fig. 15 – Predicted depth limit and EMW with 250 gpm liquid rate and minimum backpressures in a 4.75”x2.375” annulus

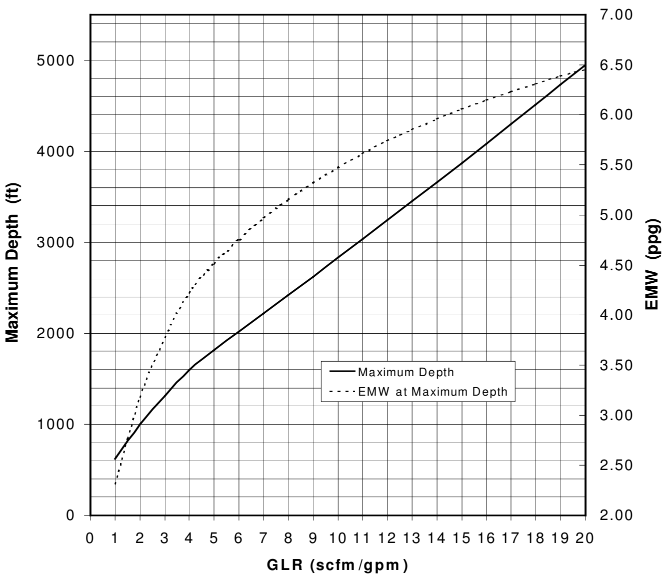

Fig. 14 – Predicted depth limit and EMW with 130 gpm liquid rate and minimum backpressures in a 4.5”x2.375” annulus