Optimization of Multiple Bit Runs Based on ROP Models and Cost Equation for One of the Persian Gulf Carbonate Reservoirs

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ABSTRACT

According to the conventional drilling cost equation, the key to minimize the drilling cost would be the increase of rate of penetration (ROP). Several ROP models have been developed and modified based on the concept of unconfined compressive strength (UCS). These models can predict the rate of penetration of different bit types in an oil or gas field with a reasonable degree of accuracy.

The ROP model derived by Warren and modified by Hareland relates the rate of penetration to operating conditions, rock strength and bit parameters. Also, the effects of hole cleaning and bit wear on rate of penetration have been included in this model. This model is capable of accurately simulating the drilling of a well and producing a reliable rate of penetration at any specific depth.

In this paper, the information from one of the Middle East carbonate fields was utilized to optimize the drilling costs for upcoming wells in this field. This has been done by creating an Apparent Rock Strength Log (ARSL) along the wellbore and developing the Modified Warren’s Model with new constants for this field. The concept of a learning curve has been used by conducting a number of simulations to obtain the optimum bit hydraulics, best combination of drilling parameters (WOB and RPM) and the most effective bit pull depth.

The approach used in this study can be used in pre-planning and post analysis to minimize the cost of drilling operations and reduce drilling costs on any development wells where wells were previously drilled.

Key Words: Drilling Optimization, Rate of Penetration Model, Apparent Rock Strength Log, Drilling Cost Equation, Drilling Simulator, Bit Run Depth.
1- INTRODUCTION

The objective of any oil company is drill and produce wells in the least possible time consistent with safe operations and environmental regulations. The effective least-cost drilling means drilling the most usable hole possible to the pay zone in the shortest time. Selecting and using the best combinations of equipments and techniques to accomplish this goal is called “Drilling Optimization”.

The main function of drilling engineer is to recommend drilling procedures concerning routine rig operations such as drilling fluid treatment, pump operation, bit selection, and any problems encountered in the drilling operation. In many cases, the use of a drilling cost equation can be useful in making these recommendations. The calculation of cost per foot is done by the conventional cost equation as follows:

\[ C_f = \frac{(t_r + t_t + t_c)C_r + t_rC_m + C_b}{\Delta D} \]  

where \( C_f \) is drilled cost per unit depth ($/ft), \( C_b \) is the cost of bit ($), \( C_m \) is downhole motor cost ($/hr) and \( C_r \) is the fixed operating cost of the rig per unit time ($/hr) independent of the alternatives being evaluated. In addition, \( \Delta D \) represents the depth drilled (ft), \( t_r \) is the bit rotating time (hr), \( t_t \) is the total trip time (hr) and \( t_c \) is the pipe connection time (hr).

According to the conventional drilling cost equation, the key to minimize the drilling cost would be the increase of rate of penetration (ROP). Based on the recorded data from the previously drilled wells in a given field, one can predict the rate of penetration in that field using a predictive ROP model. Having this predictive ROP we will have a more reliable overview on what will be going on in the future wells. Therefore, the more reliable and precise ROP model, the more practical results will be.

There are four groups of parameters that affect ROP performance of a bit. These can be divided into operational parameters, formation description, bit type and design and bit wear status. The roller cone ROP modeling work performed by Amoco research developed the first two term model, which linked WOB, RPM, bit size and rock strength. Later on, a model of the drilling process for tricone bits called perfect-cleaning model was derived by Warren \(^\text{[1]}\) and later modified by Hareland \(^\text{[2]}\). This model relates penetration rates to operating conditions, rock strength and bit parameters. Also, the effect of the hole cleaning and bit wear on rate of penetration is included in this model. One of the parameters that should be obtained along the wellbore is the rock strength. To accomplish the objectives of this study, the drilling data from offset wells have been utilized to calculate the rock strength along the wellbore. This was done by using a new Drilling Optimization Simulator called DROPS\(^\text{®}\).

To achieve the purposes of this study, a case study has been done on Salman offshore field located in the Persian Gulf.

2- DEVELOPMENT OF RATE OF PENETRATION MODELS

The rate of penetration achieved with the bit, as well as the rate of bit wear has an obvious and direct effect on the cost per foot drilled. The most important variables affecting the penetration rate that have been identified and studied include: (1) Bit type, (2) Weight on bit, (3) Rotary speed, (4) Drilling fluid properties, (5) Bit hydraulics, (6) Formation properties. A considerable amount of experimental work has been done to study the effect of these variables on drilling rate. In most of these...
experimental works, the effect of a single variable was studied while holding the other
variables constant.

Modeling ROP has been attempted since the 1960’s, but the models where not
verified with laboratory data until the late 70ties. The rate of penetration (ROP) model
describes the physical interaction between the bit and the rock as a function of the
parameters that affect the bit performance. There are four groups of parameters that
affect ROP performance of a bit. These can be divided into operational parameters,
formation description, bit type and design and bit wear status.

2.1- Perfect-Cleaning Model

A model of the drilling process for tricone bits called perfect-cleaning model was
derived by Warren [1] and later modified by Hareland [2]. This model relates ROP to
weight on bit (WOB), rotary speed, rock strength and bit size using dimensional
analysis and generalized response curves. The basic idea is that under steady-state
drilling conditions, the rate of cutting removal from the bit is equal to the rate at
which new chips are formed. This implies that the ROP is controlled by the cutting-
generation process, the cutting removal process, or a combination of the two
processes.

The perfect-cleaning model is reviewed as a starting point for development of an
imperfect-cleaning model:

\[
R = \left( \frac{aS^2d_b^2}{N^bW^2} + \frac{c}{Nd_b} \right)^{-1}
\]

The first term of equation defines the rate at which the rock is broken into small chips
by the bit. The second term of the model modifies the predictions to account for the
distribution of the applied WOB to more teeth as the WOB is increased and the teeth
penetrates deeper into the rock.

Unfortunately, ROP in most field cases is significantly inhibited by the rate of
cuttings removal from under the bit. Thus Equation 2 is not effective for predicting
field ROP without modification to account for imperfect cleaning. Therefore, it is
necessary to modify the ROP model for imperfect cleaning conditions which happen
for a real drilling situation.

The impact pressure measured under the bit can be compared with the expected
impact pressure for a circular jet impacting on a flat plate [3]:

\[
p_n = \frac{50}{1238.6} \rho d_n^2v_n^2
\]

where 1238.6 becomes 7991 when expressed in SI metric values. Theoretically, the
measured impact pressure should be independent of the nozzle size for a fixed bit size
and a fixed value of the impact force calculated from Equation 4:

\[
F_j = 0.000516 \rho qv_n
\]

where 0.000516 becomes 0.06183 when expressed in SI metric values. The increased
fluid entrainment of a jet that flows into a reverse flowing fluid is a function of the
ratio of the jet velocity to the return fluid velocity. The area available for fluid return
flow from under a roller-cone bit is equal to 15% of the total bit area. If \( A_v \) is the ratio
of the jet velocity to the fluid return velocity, then \( A_v \) (for three jets) is given by:

\[
A_v = \frac{v_n}{v_j} = \frac{0.15d_n^2}{3d_n^2}
\]
where 0.15 is 0.97 and 3 is 19.4 when expressed in SI metric values. The impact pressure obtained for various nozzles was found to be predicted by:

\[ p_n = (1 - A_v^{-0.122}) \left( \frac{50}{1238.6} \right) \rho \frac{d_n^2}{v_n} \]  

where 1238.6 becomes 7991 when expressed in SI metric values. The impact force modified for nozzle-size effects and the influence of the return flow is given by Equation 7:

\[ F_{jm} = (1 - A_v^{-0.122}) F_j \]  

2.2- Imperfect-Cleaning Model

Dimensional analysis was used to isolate a group of variables consisting of the modified impact force and the mud properties to incorporate into Equation 2 to account for the cutting removal. This results in imperfect-cleaning model:

\[ R = \left[ \left( \frac{aS^2d_b^3}{NW^2} + \frac{b}{Nd_b} + \frac{cd_b\gamma_f \mu}{F_{jm}} \right) \right]^{-1} \]  

This equation describes a continuous transition from cuttings generation to cuttings removal as the controlling factor on ROP. The model shows that the impact force must be increased as the bit size is increased to maintain a particular level of cuttings removal, but the particular nozzle size used generally becomes less important as the bit size increases.

3- MODIFIED WARREN’S MODEL

Neither Winters [4] nor Warren [1] addressed “Chip hold down effects” on penetration rate modeling, but it is known that this effect is important. To establish the best relationship for chip hold down, data from laboratory full scale drilling tests was used in which bottomhole pressure varied and other conditions remained constant. A reasonable fit to this data for different lithologies is given by:

\[ f_c(P_e) = c_e + a_e(P_e - 120)^{b_e} \]  

where \( P_e \) is the differential pressure. \( f_c(P_e) \) is defined as the “chip hold down function” and \( a_e, b_e \) and \( c_e \) are lithology-dependent constants and have been given in Table 1. Units on \( a_e, b_e \) and \( c_e \) chosen such that \( f_c(P_e) \) is dimensionless.

Equation 8 can now be modified to include chip hold down effect and becomes:

\[ R = \left[ f_c(P_e) \left( \frac{aS^2d_b^3}{NW^2} + \frac{b}{Nd_b} + \frac{cd_b\gamma_f \mu}{F_{jm}} \right) \right]^{-1} \]  

Hareland [5] modified this ROP model for the effect of bit wear on rate of penetration by introducing a wear function \( W_f \) into the model:

\[ R = W_f \left[ f_c(P_e) \left( \frac{aS^2d_b^3}{NW^2} + \frac{b}{Nd_b} + \frac{cd_b\gamma_f \mu}{F_{jm}} \right) \right]^{-1} \]  

\[ W_f = 1 - \frac{\Delta BG}{8} \]
where $\Delta BG$ is the change in bit tooth wear. It can be calculated based on the WOB, ROP, relative rock abrasiveness and confined rock strength.

$$\Delta BG = W \sum_{i=1}^{n} WOB_i \times RPM_i \times Ar_{abr} \times S_i$$

(13)

Rock compressive strength is a function pressure and lithology:

$$S = S_0 \left(1 + a_s P_r^b \right)$$

(14)

where, $S$ and $S_o$ are the confined rock strength and unconfined rock strength, respectively. The coefficients $a_s$ and $b_s$ depend on the formation permeability and are shown in Table 1.

Table 1- Chip Hold-down Permeability Coefficients

<table>
<thead>
<tr>
<th>Formation</th>
<th>Permeable</th>
<th>Impermeable</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_c$</td>
<td>$P_h - P_p$</td>
<td>$P_h$</td>
</tr>
<tr>
<td>$a_c$</td>
<td>0.00497</td>
<td>0.0141</td>
</tr>
<tr>
<td>$b_c$</td>
<td>0.757</td>
<td>0.470</td>
</tr>
<tr>
<td>$c_c$</td>
<td>0.103</td>
<td>0.569</td>
</tr>
<tr>
<td>$a_s$</td>
<td>0.0133</td>
<td>0.00432</td>
</tr>
<tr>
<td>$b_s$</td>
<td>0.577</td>
<td>0.782</td>
</tr>
</tbody>
</table>

3.1- Apparent Rock Strength Log

According to Warren’s ROP model, one the parameters that should be obtain along the well bore is the rock strength. It is critical to obtain the rock strength parameters along the wellbore. Different sources can be used to develop rock strength information. Such strength information is important when assessing the stability of the wellbore, selecting the mud weight and designing casing programs. To obtain the rock strength along the wellbore, petrophysical logs, rock mechanical laboratory tests and rock mechanical tests on small cutting samples can be used. Rock mechanical laboratory testing on preserved core samples are the most accurate method for calculating rock strength. However, the disadvantage of this method is that well preserved core samples for conducting laboratory measurements are rare and the testing procedure is time consuming. On the other hand, the logs are only available in the reservoir sections of the wells which will limit the availability of continuous rock strength along the wellbore.

One source of data which is often overlooked in calculating rock strength is drilling data. The advantage of using drilling data to calculate rock strength is that they are available for the whole well not only the reservoir zones. Also, they are directly connected to the predictive ROP model. To utilize the drilling data in calculating rock strength, correlations are developed from inverted rate of penetration models. From these models, unconfined compressive rock strength can be calculated from drilling data.
4- FIELD STUDY

To accomplish the objectives of this study, a case study has been conducted on Salman offshore field located in Persian Gulf. Four wells, namely A, B, C and D carry the most available data for this study. Hence they were chosen for this research.

4.1- Data Gathering and Study of Salman Field

The data gathering and study phase builds a knowledge base of the facts and experiences gained while drilling in a particular area. All offset well data are studied to identify potential problems. The goal is to minimize or eliminate these problems and establish limits based on information acquired from the study and equipment used while drilling.

To achieve the objectives of this study, it is not a good practice to analyze all the sections of the proposed well. Therefore, a section of the well A was selected. Availability of the data and the impact of the cost optimization on the well profitability were two criteria which were considered for choosing of this section.

The section 12¼-in. of well A, (Hith-Surme formation down way to Dashtak formation) accomplished all criteria. The drilling parameters, bit properties, and a good interpolation of pore pressure were available for each meter. The bit types used for this section were predominantly three-cone with some PDC bits. The lithology was available every meter which allowed good formation characterization. On the other hand, this section represented approximately 40% of the total time for well construction and the total cost. Therefore, the economical viability of this field requires a strong improvement of the drilling operations in these sections, with a consistent reduction of time and cost.

4.2- Generation and Validation of Apparent Rock Strength Log

The next phase involves selecting a reference well which closely matches the planned well. Using the data from the reference well, an Apparent Rock Strength Log (ARSL) is generated by the inversion of the rate-of-penetration model. The effects of drilling hydraulics, mud rheology, and pore pressure are integral to the model.

The inverted rate of penetration provides a calibrated measure of rock strength under actual drilling conditions and simultaneously determines the wear characteristics of the bits used in drilling each section. This wear characteristic is a statistical evaluation of the bits' performance while drilling different formation types under a variety of operating conditions and includes detailed bit geometry and resistance to wear.

To accomplish the objectives of this study, the drilling data from offset wells have been utilized to calculate the rock strength along the wellbore. This was done by using a new Drilling Optimization Simulator called DROPS®. This simulator is based on penetration rate models and uses offset drilling data through inverted drilling models to obtain an apparent rock strength log (ARSL), which describes the drillability in a field or area. In addition, this simulator has the capability of simulating any combination of operating conditions, bit designs; pull depths, hydraulics, WOB (Weight on Bit) and RPM. The basic idea behind DROPS® is to simulate the drilling operation prior to the actual drilling, and to find the optimum cost level.

DROPS® requires three groups of data to generate the apparent rock strength log. These data are: (1) <BITFILE>.bit, which contains the detailed information about the drill bits that were actually used in a particular section. (2) <DRILLFILE>.drill, which contain all relevant operating parameters and other data for the particular
<LITHFILE>.lith which contain all relevant information about the types of formations in the selected section.

Once the program has generated the ARSL, it verifies its accuracy according to the relevant theoretical ROP models by performing a drill-behind. The drill-behind conducts a reverse ARSL calculation, where the calculated apparent rock strength is used to calculate the theoretical ROP. This ROP is then compared to the field reported ROP. Figure 1 shows a schematic plot of DROPS® Drilling Simulator generated for 12 ¼ in. and 8 ½ in. sections, well A. The second column shows the ARSL for these sections.

The quality of the ARSL is dependent of the input files where it was generated. This means that the simulation will not be more accurate than the ARSL. A good approach to verify the ARSL accuracy and come up with a more reliable rock strength values would be fine tuning the values of ARSL from the reference well with the ARSL from the other wells in the same field. In fact, some of the errors happening in the ARSL log creation are more difficult to see and understand. Therefore, it helps when more than one reference well is available. In this study, in addition to well A which was considered as the reference well, wells B and C were used to conduct the ARSL comparison. The ARSL was independently generated for all three wells and the result overlain on a true vertical depth basis. While there are local variations in the ARSL values generated and some uncertainty in predicting the occurrence of geological structure, there is a remarkable correlation.

Figure 1- Schematic Plot of 12 ¼ in. and 8 ½ in. Sections in DROPS®, Well A.
4.3- Development of the ROP model for Salman Field

After tuning the values of ARSL with the offset wells, the resulted ARSL can be considered as unconfined compressive strength (UCS), $S_o$. Then solving Equation 8 for confined compressive strength $S$ yields:

$$S = \left( \frac{NW^2}{af_c(P)Rd_b^3} - \frac{bW^2}{ad_b^4} - \frac{c\gamma_f \mu NW^2}{af_c(P)I_n d_b^2} \right)^{0.5}$$ \quad \text{(15)}

which is the input of ROP model.

As it was discussed before, the coefficients and constants used in Warren’s model can be classified into three categories:

- Coefficient $a_c$, $b_c$ and $c_c$ are lithology-dependent constants and are given in Table 1. Units on $a_c$, $b_c$ and $c_c$ chosen such that $f_c(P)$ is dimensionless (Equation 9).
- Coefficients $a$, $b$ and $c$ depend on the formation permeability and are shown in Table 1.
- Coefficients $a$, $b$ and $c$ are bit coefficients and can be determined by a simple dimensional analysis. The dimensionless group $ND/R$ can be plotted versus $S^2 D^4/W^2$. The least-squares method was used to fit a straight line to the data with a resulting slope of $a$ and interception of $b$. The resulted bit constants have been presented in Table 2.
- Bit wear coefficients, $W_c$, which is a coefficient for bit grade change, $\Delta BG$ (Equation 13). This coefficient is a unique number for each bit run and can be determined according to the dull condition of the corresponding bit. The derived bit wear coefficients for each bit run have been listed in Table 2.
- Bit wear function, $W_f$, which is a number between zero and one and changes with bit wear grade change, $\Delta BG$ (Equation 12). This means that $W_f$ becomes one for a green bit ($\Delta BG = 0$) and zero for a completely worn bit ($\Delta BG = 1$).

<table>
<thead>
<tr>
<th>Bit Run No.</th>
<th>Bit Wear Coefficient ($W_c$)</th>
<th>3-Term ROP Model Bit Coefficients</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$a$</td>
</tr>
<tr>
<td>1</td>
<td>$5.64 \times 10^{-10}$</td>
<td>0.0019</td>
</tr>
<tr>
<td>2</td>
<td>$2.36 \times 10^{-10}$</td>
<td>0.0011</td>
</tr>
<tr>
<td>3</td>
<td>$3.96 \times 10^{-10}$</td>
<td>$3.0 \times 10^{-5}$</td>
</tr>
<tr>
<td>4</td>
<td>$7.90 \times 10^{-10}$</td>
<td>0.0004</td>
</tr>
<tr>
<td>5</td>
<td>$1.82 \times 10^{-10}$</td>
<td>$6.0 \times 10^{-4}$</td>
</tr>
<tr>
<td>6</td>
<td>$5.35 \times 10^{-10}$</td>
<td>0.0026</td>
</tr>
<tr>
<td>7</td>
<td>$2.29 \times 10^{-11}$</td>
<td>$3.0 \times 10^{-4}$</td>
</tr>
<tr>
<td>8</td>
<td>$3.35 \times 10^{-11}$</td>
<td>0.0002</td>
</tr>
<tr>
<td>9</td>
<td>$2.43 \times 10^{-9}$</td>
<td>0.0060</td>
</tr>
<tr>
<td>10</td>
<td>$1.83 \times 10^{-9}$</td>
<td>0.0060</td>
</tr>
<tr>
<td>11</td>
<td>$3.92 \times 10^{-10}$</td>
<td>0.0066</td>
</tr>
<tr>
<td>12</td>
<td>$5.59 \times 10^{-10}$</td>
<td>0.0023</td>
</tr>
<tr>
<td>13</td>
<td>$4.27 \times 10^{-10}$</td>
<td>0.0023</td>
</tr>
</tbody>
</table>
After determining the various coefficients within the ROP model, and knowing the operating parameters, bit properties and mud properties, rate of penetration (ROP) might be calculated at any particular depth. This rate of penetration is called $\text{ROP}_{\text{model}}$. This ROP does not represent the real rate of penetration resulted from the ROP model. It should be modified for the effect of field parameters. In order to take into account the effect of field parameters, the rate of penetration predicted from the model should be correlated with the actual rate of penetration recorded in the field. This means that $\text{ROP}_{\text{model}}$ should be multiplied by a constant $K$ called matching coefficient:

$$\text{ROP}_{\text{match}} = \text{ROP}_{\text{model}} \times K \quad \text{................................................................. (16)}$$

Total rotating time of based on $\text{ROP}_{\text{match}}$ should be equal to the total rotating time of based on $\text{ROP}_{\text{field}}$. The matching coefficients $K$ are then fixed for each bit run. The results have been listed in Table 3.

### Table 3- ROP Matching Coefficients for Different Bit Runs

<table>
<thead>
<tr>
<th>Bit Run No.</th>
<th>Matching Coefficient (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.019</td>
</tr>
<tr>
<td>2</td>
<td>8.314</td>
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<tr>
<td>3</td>
<td>3.485</td>
</tr>
<tr>
<td>4</td>
<td>3.138</td>
</tr>
<tr>
<td>5</td>
<td>2.207</td>
</tr>
<tr>
<td>6</td>
<td>1.547</td>
</tr>
<tr>
<td>7</td>
<td>2.889</td>
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<td>8</td>
<td>3.066</td>
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<td>9</td>
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<td>10</td>
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<td>12</td>
<td>4.134</td>
</tr>
<tr>
<td>13</td>
<td>3.681</td>
</tr>
</tbody>
</table>

#### 4.4- Optimization of Drilling Hydraulics

Optimization of drilling hydraulic for well A includes the selection of best nozzle size of each bit to achieve the maximum rate of penetration. The maximum bit hydraulic horsepower (BHHP) criteria was assumed as the criteria for optimizing bit hydraulics. According to this criterion, for optimum hydraulics, the pressure drop across the bit should be 65% of the total available surface pressure.

Table 4 compares the total rotating time after hydraulic optimization with the actual rotating time recorded in the field. It shows a reduction of 25% of total rotating time in 12 ¼ in. section.

#### 4.5- Optimization of WOB and RPM

More than 100 simulations have been conducted for 12 ¼ in. section to obtain the optimum combination of WOB and RPM for each bit run. It was assumed that the rotary speed more than 350 rev/min and weight on bit more that 50MT can not be utilized due to rig capabilities. Table 4 shows the results of total rotating time after optimization of WOB and RPM for each bit run. The figures show a reduction of 40% of total rotating time.
4.6- Cost Analysis

The calculated total rotating time after each simulation has been applied to compute the total cost and cost per meter according to the conventional cost equation (Equation 1) with appropriate bits and operating costs. The best cost is then determined as shown in Figure 2. Table 4 represents the calculated total cost and cost per meter for each simulation. In addition, Figure 2 is the learning curve for 12 ¼ in. section which shows the variation of total cost and cost per meter for each simulation in this interval.

Table 4- Total Cost and Cost per Meter for Each Simulation in 12 ¼ in. Section, Well A

<table>
<thead>
<tr>
<th>Simulation No.</th>
<th>Total Rotating Time (hr)</th>
<th>Total Cost ($)</th>
<th>Cost/m ($/m)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>440.15</td>
<td>1559712</td>
<td>1182</td>
<td>Drill Behind</td>
</tr>
<tr>
<td>1</td>
<td>437.86</td>
<td>1555429</td>
<td>1179</td>
<td>Optimum Nozzle Size for Bit No.1</td>
</tr>
<tr>
<td>2</td>
<td>436.78</td>
<td>1553403</td>
<td>1178</td>
<td>Optimum Nozzle Size for Bits No.1-2</td>
</tr>
<tr>
<td>3</td>
<td>435.79</td>
<td>1551547</td>
<td>1176</td>
<td>Optimum Nozzle Size for Bits No.1-3</td>
</tr>
<tr>
<td>4</td>
<td>428.58</td>
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<td>1166</td>
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<tr>
<td>5</td>
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<tr>
<td>6</td>
<td>405.26</td>
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<tr>
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<td>403.43</td>
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<td>8</td>
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<td>12</td>
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Figure 2- Learning Curve for 12 ¼ in. Section, Well A
5- CONCLUSIONS AND RECOMMENDATIONS

The following conclusions have been made from this study:

- This study was performed to evaluate the benefits of drilling optimization based on Modified Warren’s ROP model.
- Based on the proposed model for rate of penetration, a simple and useful simulator has been developed. This simulator works based on the creation and use of an Apparent Rock Strength Log (ARSL).
- The creation and use of an ARSL was effective in drilling cost optimization. This rock strength log for a specific field can be created using the drilling data of the previously drilled wells in that field. This can be done using DROPS® Drilling Simulator.
- This study shows that using a greater WOB and smaller RPM than what have been used in well A and selecting smaller nozzle sizes can significantly increase the rate of penetration in Salman field. In addition, the drill bits used in well A seem to be effective in increasing the rate of penetration. However, using more aggressive bit (higher IADC codes) is beneficial, if possible.

We recommend the following:

- In this study, the values of ARSL were correlated by the rock strength logs from the other well in the same field. It is recommended that this rock strength log is correlated with sonic data. This leads to generate a more precise rock strength values.
- DROPS® Drilling Simulator as an optimization tool can be utilized to propose a drilling optimization plan for well A. The results from this simulator may be compared with the results of this study to come up with a final drilling optimization program for mud weight, bit hydraulics, WOB and RPM combination and bit pull depth.

6- ACKNOWLEDGEMENT

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7- REFERENCES