# EXPERIMENTAL VERIFICATION OF A DRILLING SIMULATOR.

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## ABSTRACT

A computer Drilling Simulator has been verified and modified by comparison with laboratory data. The starting point was to obtain laboratory records that contained a complete set of data needed for simulation, e.g. weight on bit, flow rate, revolution per minute…etc. These data were used as input for the simulator in order to have predictions of the rate of penetration as an output. The predictions were illustrated as curves that show the response of the rate of penetration to the change in weight on bit. The data enabled a three-way comparison to be made whereby the laboratory drilling data were compared with the predictions of the drilling simulator and with the predictions of a well-known model (Warren, Winters, and Onyia). The simulator was tuned so that it reproduced the laboratory drilling records as closely as possible. For the particular set of records that were used, it was found that for milled tooth, tungsten carbide, and diamond impregnated bits, the simulator needed modifications in some constants but then gave a good correspondence with the experimental data. This indicated the simulator is suitable for the prediction of the rate of penetration during drilling provided that the proper constants are used.

## Introduction

There have been numerous attempts to use simulators to improve the drilling of hydrocarbon wells (1-5) but none has yet been widely accepted. This may partly be because of the complexity of the drilling process. It results, on the one hand, in a requirement to collect a large amount of data before a good simulation can be made of a specific well, and on the other, the need for the operator of the simulator to be highly skilled in using the data to best advantage.

Simulators have, however, been used more successfully in training, (6,7) where it has been found that it is relatively straightforward to illustrate the general principles of drilling operations if there is no requirement that the simulation should exactly match the drilling behavior of a particular well. To try to bridge this gap, we have used a simulator that was originally developed for training purposes and have verified its output to reproduce a realistic prediction of the drilling behavior in a real well. Once the simulator was tuned, we used it to investigate the effects of re-drilling the well using different operating parameters to see if better results might be obtained under other conditions.

The simulator (called "Payzone" for short), is a computer program that receives: a description of a series of rock layers (a "lithology"), a description of one or more drill bits, and a set of operating parameters such as weight on bit, bit rotary speed, mud flow rate and other required information, as input. The simulator then calculates the rate of penetration and the rate of wear of the bit. From this information, a plot of drilled depth versus time is obtained. The simulator can be tuned to represent a range of field conditions by adjusting the characteristics of the bit and lithology and by changing the algorithm that makes the necessary calculations. The basic equations for the rate of penetration in the Payzone algorithm are:

*Ideal ROP = Constant X Aggressivity factor X RPM X Tooth Length X G* ----------- Eq. 1
*G = 1-exp {- [(WOB / Sig) ^ Curvature] X [12 / ((BitD^2.5) X (0.4 X Tooth Length))]}*-- Eq. 2

*Real ROP = Ideal ROP X Flow Factor*---------Eq. 3

*Where:*
*RPM* is the rotary speed.
*WOB* is the weight on bit.
*Tooth length* is average tooth length of the bit.
*Bit D* is the bit diameter.
*Sig* is the rock strength of the formation at a certain differential pressure.
*Ideal ROP* is the rate of penetration that would be obtained under conditions of perfect cleaning of the hole.
The *Flow Factor* is a factor to reduce ROP as a compensation for non-perfect cleaning conditions.
*Real ROP* is the real rate of penetration after compensating for the non-perfect cleaning conditions.
*Aggressivity* and c*urvature* will be explained shortly.

In the original formulation of the Payzone model, the overall equation (Eq. 1) was based on a physical model for the process of breaking the rock under a drill bit (9). However, there had to be some adjustable tuning constants. These were adjusted to make the model correspond exactly with a set of lab data. This data set had also been used to develop a widely recognized drilling model published by Warren, Winters and Onyia, (8), (referred to hereafter as the WWO model). Thus, at the beginning of this study, the Payzone drilling model corresponded closely with the WWO model, and also with the original data set from which it had been derived. However, the data set concerned only a limited number of test conditions. A major objective of the current work was therefore to examine if the Payzone model could be made to fit a much wider range of bit types and operating conditions.

It was observed that the WWO Rop equation had a physical flaw. This flaw results from the fact that their final Rop depends on the summation of four different terms (8). This means that if one of these terms disappears such that, physically, the Rop would not exist, the other terms will still indicate a significant Rop value. For example, if their hydraulics term disappears, which means that there is no Rop (since there would be no flow of mud to remove the cuttings), the other terms in their main equation will still give a significant Rop value. On the other hand, the Payzone model has a more physical touch as it links all the parameters together as can be seen in equations 1 through 3.

The theoretical Rop of the original model was modified (reduced) by the influence of the mudflow that cleans the hole bottom (Eq. 3). This allowed for the fact that if the cuttings are removed less than instantaneously from the hole bottom, the Rop is reduced because of the choking effect of the cuttings that remain on the bottom of the hole.

The aggressivity factor (Eq. 1) is a constant to adapt the values of Rop to different bits and to different formations. The aggressivity factor has a nominal value of 100 that was assumed correct for a milled-tooth bit drilling in shale. These conditions corresponded exactly with those used to obtain the WWO lab data. The aggressivity factor simply multiplies the value of the calculated Rop before adjustments are made for the efficiency of cleaning the hole. Thus, changes to the aggressivity factor typically cause changes to the gradient of the Rop versus Wob plots, and may be thought of as expressing the difference between “sharp” and “blunt” bit types.

The curvature constant (Eq. 1) is an exponential factor of (Wob / Rock strength) to the power of 1.5. This factor determines the shape of the plot of Rop versus Wob before hole-cleaning factors are included, such that its effects are mainly noticeable for conditions of good hole cleaning, that is, at low Wob or Rpm. In the original model, the curvature value was set to 1.5, where it causes Rop to rise exponentially, at low weights. Physically, the curvature expresses the fact that because the teeth of a real drill bit are not infinitely sharp, the rate of penetration of the bit at very low weight is unexpectedly low. This is because, at low weight, the only parts of the bit teeth that penetrate the rock are the rounded ends of the teeth, with the result that the bit appears to be blunt. As the weight increases, the teeth penetrate more deeply, and overall, the bit appears to become sharper. Hence, a plot of Rop vs. Wob shows an increasing gradient, that is conveniently modeled by raising the Wob to a power greater than unity.

The main concern of this study is principally to observe the change in the adjustable constants, aggressivity factor and curvature (Eq. 1), in order to see whether there is any consistency in their values and if these values change due to a certain change in parameters. Accordingly, one can determine the type of model modification required, i.e. whether the model needs physical modification or whether a change of the values of these constants would be sufficient. The main goal is to obtain a general equation that calculates the rate of penetration as a result of changes in the various parameters (Weight on bit, revolutions per minute, flow rate, nozzle size…etc.) without changing the equation for each set of parameters. This will be done by curve fitting and trial and error of different data with different constant values, until one or two values appear to have good results. Then these values can be verified against the data.

## Preview of data

Three sets of data from two different sources were used in verifying the simulator: Two sets of data were Laboratory tests from Hughes Christensen (a drill bit manufacturer). These data included results of some tests done on a drilling machine that simulates down hole conditions.

The third set of data was test data from SPE publications. These data were obtained from an SPE paper (12) that contained the average results from tests done on drilling test machines that simulate down hole conditions (on four different TCI bit sizes 6.5'', 7.875", 9.5" and 11"). Having data from two different laboratories gave confidence in the outcome of the study.

## ***Study***

For economy of space, only some of the tests that were done will be presented. The data contained the type of rock used, bit type, nozzles, drilling parameters (weight on bit, rate of penetration, revolutions per minute, flow rate, and mud weight, which are denoted hereafter as Wob, Rop, Rpm, flow rate, and Mwt respectively), time increments that the tests were recorded at, pressure, and mud type. The rock strengths of the formation samples were not reported in the paper; therefore, they were obtained from the literature (13).

There are four main bit types, namely, Milled tooth, Tungsten Carbide, Polycrystalline Diamond Compact, and Diamond-Impregnated bits. These types of bits will be denoted hereafter as MT, TCI, PDC, and DImp respectively. The main output of the tests that were in the data sets was the response of the rate of penetration as a function of weight on bit, with the rest of the parameters kept constant for a particular test.

The data enabled a three-way comparison to be made whereby the laboratory drilling data were compared with the predictions of the drilling model in the Payzone simulator and with the predictions of the WWO model. Since the objective was to compare the two drilling models, it was not desirable to go through the process of running a full simulation each time, since this is very time consuming. Instead, a small program was built using "Matlab" in which the drilling algorithm used in the Payzone simulator was used to generate one set of results while the WWO algorithm was used to generate a second set. These were simultaneously presented graphically and compared with the laboratory data on a single graph. This allowed the change of one or more factors at a time in the Payzone model (the aggressivity factor or the curvature). In this way, the effect of each change could be observed.

The differential pressure (borehole pressure less the pore pressure) of the formation was not completely identified in the data received. The problem was that the pore pressures of the rocks used in the tests were not available. Hughes Christensen does not have the pore pressure or the rock strength data for the tests. Hence, some assumptions were made depending on the permeability of each rock. Since anhydrite, shale, and Carthage Marble have very low permeability (from $<10^{-6}$ to $1.7*10^{-6}$ Darcy), the assumption was that the differential pressure equaled the bottom hole pressure. In other words, the pore pressure has no significance due to the small permeability, i.e. the pore pressure would be considered zero for calculation purposes. The permeability of the Crab Orchard Sandstone is not small enough to ignore the effects of the pore pressure. In fact, the pore pressure of the sand is very important because mostly it is the reservoir rock. Thus, for tests done using sandstone, an assumption of the differential pressure was made for each particular test. This assumption will be further discussed below.

The WWO model was built on the results of tests done on soft shale at low pressure (1200 Psi), therefore a change had to be made to the WWO model, in order to compare the two models at different pressures. This change converts the rock strength of the rock sample to an equivalent strength at the bottom hole pressure of the particular test.

## Presentation of Results

The results of the Matlab calculations are presented on graphs that show the experimental data points as the intersections of ordinate and abscissa lines on the graphs. These data are then compared with two curves that represent the predictions of the Payzone model (dashed) and the predictions of the WWO model (continuous), respectively. The parameters that were used on each test were printed on the corresponding graph. The tooth lengths of the bits were calculated according to their IADC codes. The strengths of the rocks used in the tests are shown in Table 1. Payzone converts this rock strength to an equivalent at the pressure applied in each test.

| Rock type | Rock strength (UCS), psi |
|---|---|
| Catoosa Shale | 3,200 |
| Mancos Shale | 9,000 |
| Carthage Marble | 14,500 |
| Anhydrite | 15,000 |
| Crab Orchard Sandstone | 37,300 |

Table 1, test rock strengths

## ***<u>Comments on the different data sets</u>***

*Graphs are shown at the end of the paper*

### *The Hughes Christensen data (TCI & MT bits)*

As shown in figures 1-4: -

1. Payzone shows a better fit to the lab data points than the WWO model.
2. Payzone over-predicts the lab data by a factor of approximately three; this is shown by the aggressivity factor being approximately one third of its nominal value (100).
3. It was observed that when using the 1.5-curvature value, the rate of increase of Rop with respect to the Wob is less than that when the 1.1 value was used, at low Wob.
4. A main difference between the two models was the asymptotic limit of Rop in the Payzone prediction curve, which does not appear in the WWO model. That is due to taking into consideration the effect of tooth length in the Payzone model (Eq.1),

which was not considered in the WWO model.

***The SPE published data:*** *(TCI bits)*

As shown in figures 5-12: -

1- The shape of the gradient of Rop versus Wob is constant for a certain bit type, but changes its steepness (at low Wob) as the bit size changes. I.e. the curvature value changes from 1.5 to 1.1 as the bit size increases from 6.5 to 11", respectively. It is worth mentioning that both curvature values gave good fits to the data points for the 9-1/2" bit size, which can be considered as a transition bit size for the curvature value. Hence, this can be accounted for in the model via a **linear relationship** between the curvature value and the bit size. The new Rop equation then becomes

$$Ideal\ ROP = C1 \times Aggressivity\ factor \times RPM \times (1/(RPM + C2)) \times Tooth\ Length \times (1-\exp\{-[(WOB / Sig)^{(C3 \times BitD)}] \times [C4 \times ((BitD^{C5}) \times Tooth\ Length)]\})$$ ------- Eq. 4

*In this equation, the curvature was substituted by the BitD multiplied by a constant, instead of being 1.5. (C1, C2, C3, C4 and C5 are constants)*

2- From this change in the curvature value, it can be concluded that, at low Wob, the Rop produced by small diameter bits is less than the Rop produced by large diameter bits. This is shown from the difference in the steepness of the 1.1 and 1.5 curvature profiles, at low Wob. The physical meaning of this would be that the smaller the teeth of the bit (as the bit size decreases), the less crater volume produced at a particular Wob. Conversely, the bigger the teeth of the bit (as the bit size increases), the more crater volume is produced at a particular Wob.

3- The value of the aggressivity factor changed from 25 to 40 in all the tests that were obtained from the SPE paper. The average was approximately 35. This means that Payzone over predicts three times more than the laboratory values for TCI bits. This result was also obtained when matching the Payzone model with the Hughes Christensen lab data tests (TCI & MT bits), which shows consistency in the value of the aggressivity factor for a certain type of bit. This is a good indication of the correctness of the model.

4- It was observed that the aggressivity factor decreased as the flow rate decreased to below the minimum acceptable for cleaning the particular hole size. This means that Payzone over predicts the Rop for insufficient cleaning conditions. However, it is important to mention that insufficient cleaning conditions are forbidden in field operations.

5- The aggressivity factor also decreased when the Rpm increased at constant flow rate, which leads to the increase in the amount of cuttings. However, this decrease in aggressivity factor came to a limit as the Rpm was increased from 120 to 180, implying a saturation of Rop with respect to an increase in Rpm, hence, no increase in the amount of cuttings.

6- It was found that the variation in the aggressivity factor was + or - 10% from the value of 35, which is an acceptable value. Hence, it could be concluded that the Payzone predictions are consistent, which is a good indication of the Payzone model being valid for field purposes using TCI and MT bits.

### *The Hughes Christensen data (Diamond Impregnated bits)*

As shown in figures 13 & 14: -
Payzone has a good prediction for Rop when using Diamond Impregnated bits, especially with the linear equation curve. In other words, the same model that is used for the TCI and MT bits predicts very well when drilling with DImp bits. The aggressivity factor might be changed to a reference of around 55.

## General Comments & Conclusions

Drilling is not an exact science in general; but more of an art. However, the closer we get to predicting the Rop in a development well, whether we use an empirical, semi empirical or explicit approach, the more accurate the economic and technical analyses will be.

In this study, Payzone gave a good fit to lab data that were obtained from diverse sources. However, it needed some modification for the response of Rop with respect to the Wob, especially at low values of weight on bit. This is quite clear from the modification of the curvature and aggressivity factor values mentioned above.

One striking feature of all the comparisons is that the Payzone algorithm almost always over-predicts the bit's rate of penetration, and to a broadly similar degree in experiments in different laboratories, in different rocks and with different types of drill bit. However, the original formulation of the Payzone Rop algorithm was matched both to the WWO model and, more importantly, to the underlying experimental data from which the WWO model was derived. This therefore implies that there is some significant difference between the data from which the WWO model was derived and all the other experiments.

Warren, Winters, and Onyia made their tests on Catoosa shale at a borehole pressure of 1200 Psi, using milled tooth bits. It is well known that the drilling Rop is reduced as the borehole pressure increases (10,11). However, Warren, Winters and Onyia do not explicitly state in their paper whether they used the atmospheric pressure rock strength in their model or an increased value to allow for the fact that their experiments were carried out at a borehole pressure of 1200 Psi. For example, they stated that they used Catoosa shale, whose unconfined compressive strength has been quoted in the literature as being about 3200 Psi (13) whereas elsewhere they mentioned that they used a value for the rock strength of 8000 Psi. The Payzone algorithm, on the other hand, starts from a knowledge of the unconfined rock compressive strength (UCS) and calculates the increase in that value as a result of any increased borehole pressure.

It is possible that in the original process of deriving their model, Warren, Winters and Onyia obtained a formulation that gave a correct prediction of Rop for a rock of strength 8000 Psi but wrote (as they did) that the result had been obtained for Catoosa shale, (whose UCS is 3200 Psi). If this were so, the Rop obtained by another researcher entering a value of 3200psi into their formula would have been much higher than the actual experimental value. Since, to a very loose approximation, Rop is inversely proportional to rock strength, this effect would have had the result of over-predicting Rop by about 8000/3200 = 2.5 times, requiring multiplying the calculated result by a correction factor of 0.4 to obtain the true value.

The same correction factor would also have been required to adjust the prediction of any other drilling model (including the Payzone model) that had been tuned to match the WWO model. This is approximately the degree of over-prediction that was found in the present series of comparisons. Unfortunately, attempts to resolve the question have been unsuccessful as the published papers are not clear and it has not been possible to contact the research workers themselves directly.

The aggressivity factor (Eq. 1) and the curvature were constants of Payzone that resulted from fitting the model to the WWO data. The nominal values of these constants were 100 and 1.5, respectively. It was realized that, in order to adapt for other data, at different conditions, these constants had to be changed.

The change of the aggressivity factor value typically causes changes in the gradient of the Rop versus Wob plots, but the profile of the plot itself stays the same. In other words, the profile is multiplied by a number, and when this number is changed the gradient of the profile is changed.

The curvature (Eq. 1) is a factor that determines the profile steepness of the plot of Rop versus Wob before hole-cleaning factors are included. This makes its effects noticeable mainly for conditions of good hole cleaning, that is, at low Wob or Rpm. In the original model, the value was set at 1.5, where it causes Rop to rise more steeply than linearly at low weights. As this value decreases, the Rop versus Wob curve gets steeper.

As a conclusion of the previous analyses, of the three types of bits (Milled tooth, Tungsten Carbide Insert, and Diamond Impregnated bits) it was observed that the average aggressivity factor for each type was as follows:

MT Bits have an average aggressivity factor of 45 (it ranged from 30 to 60)

TCI Bits have an average aggressivity factor of 33 (it ranged from 26 to 40)

DImp Bits have an average aggressivity factor of 55 (it ranged from 45 to 65)

Therefore, the aggressivity factor is dependant on the bit type. It will not be difficult to change the algorithm to have a different starting aggressivity factor for each type of the bits mentioned.

## Acknowledgment

Many thanks to Mr. Aaron Dick and colleagues at Hughes Christensen for making available the experimental data on the rates of penetration of different bits

Thanks must also go to Professor A.M. Abouzeid who was always there no matter what.

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## ***Figures: -***

The figures show the parameters, the aggressivity factor and the curvature value, used. The figures on the left were tests done with a curvature of 1.5.The figures on the right were tests done with a curvature of 1.1.These two values were the main values at which the tests gave the best results. Also the figures show the parameters that were used in each test.

Figure 1

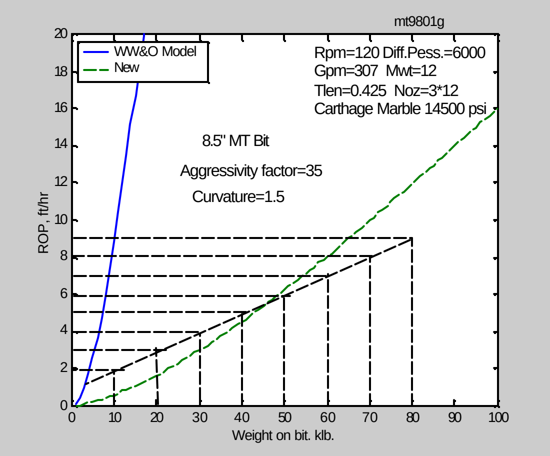
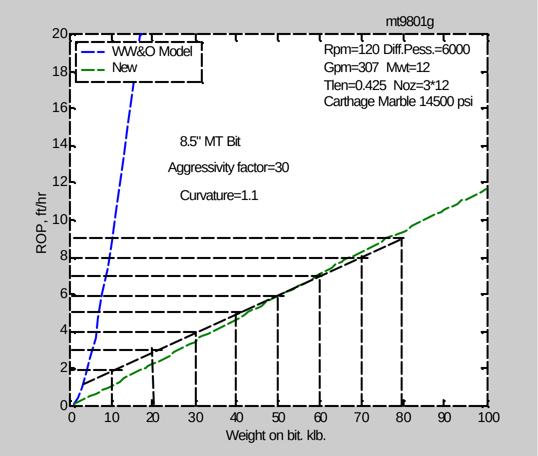


Figure 2



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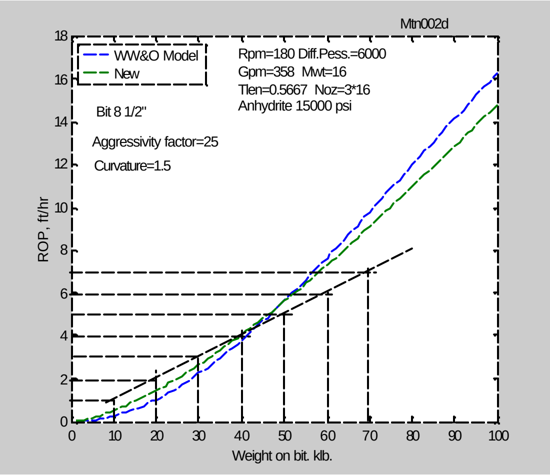

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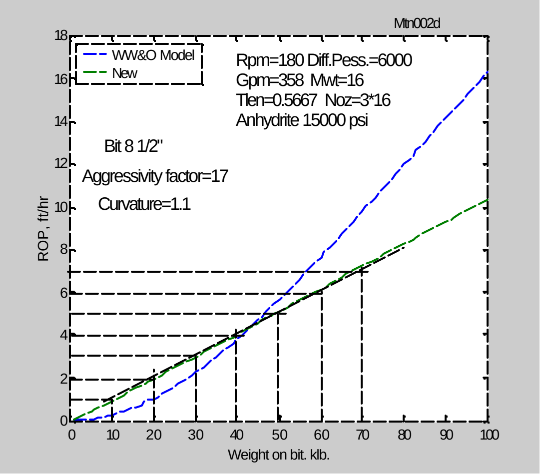

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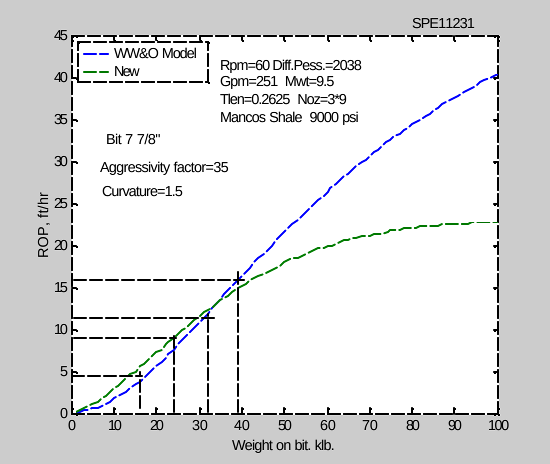

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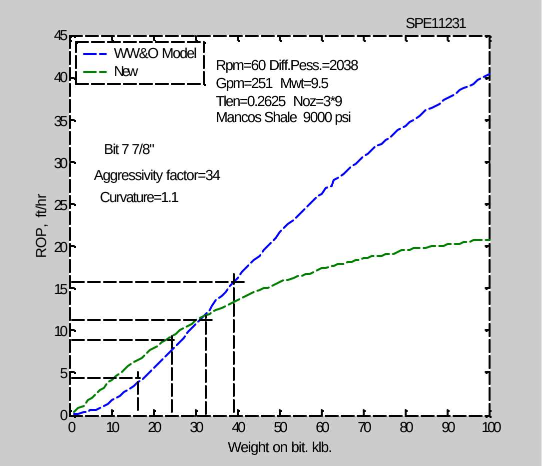

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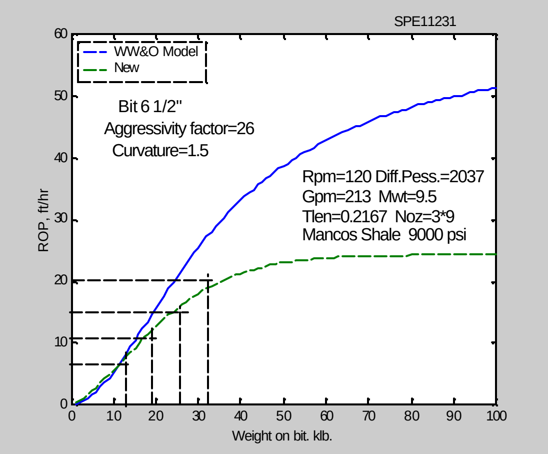


Figure 8

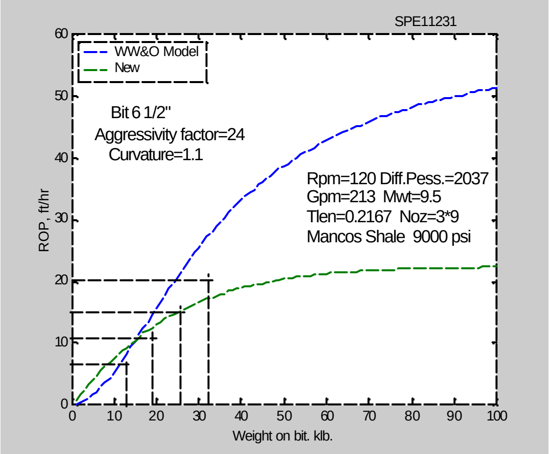


Figure 9

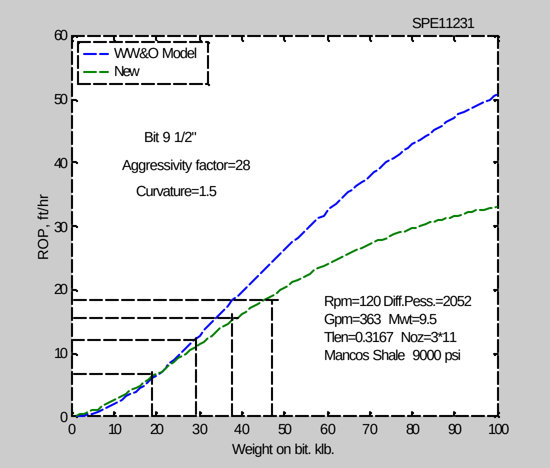


Figure 10

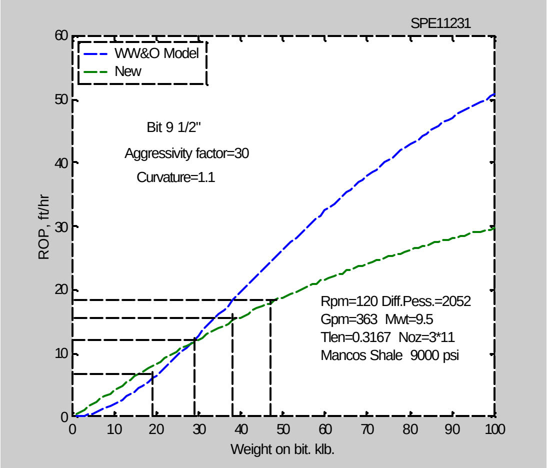


Figure 11

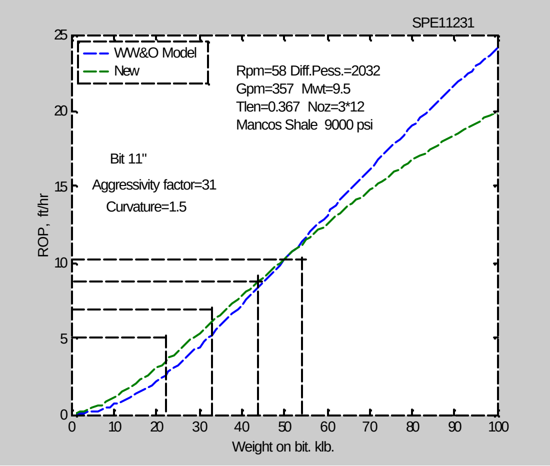


Figure 12

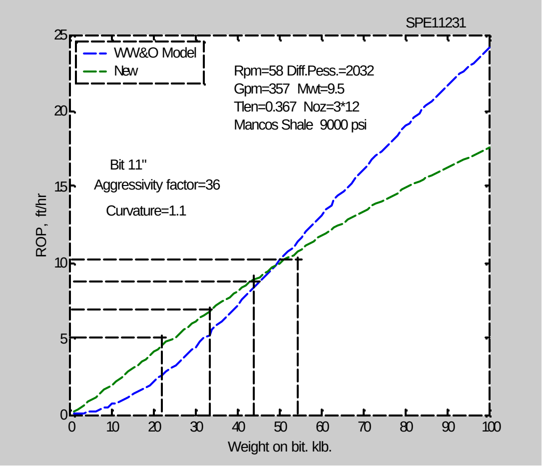


Figure 13

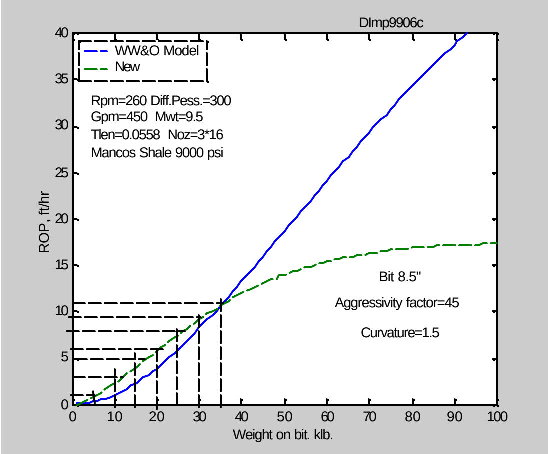
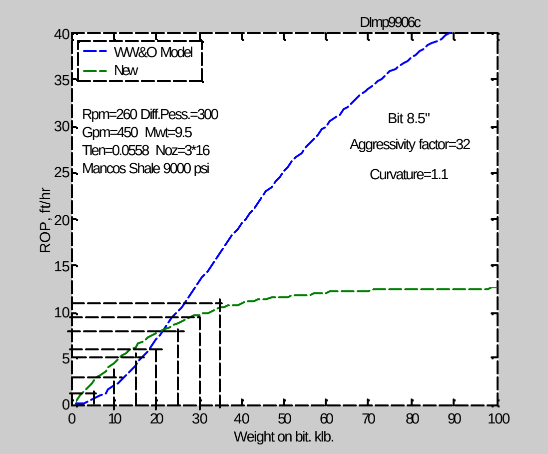


Figure 14



## Using the linear relationship

Figure 15

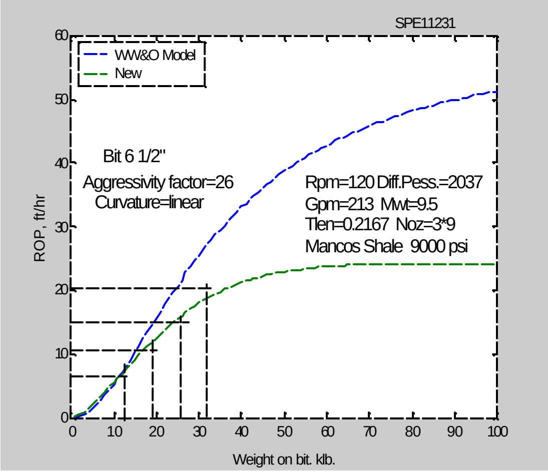


Figure 16

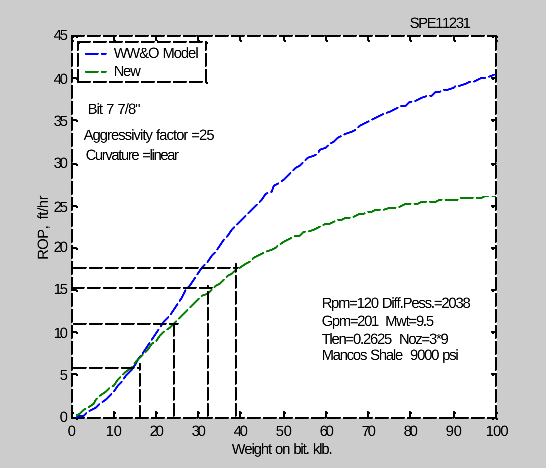


Figure 17

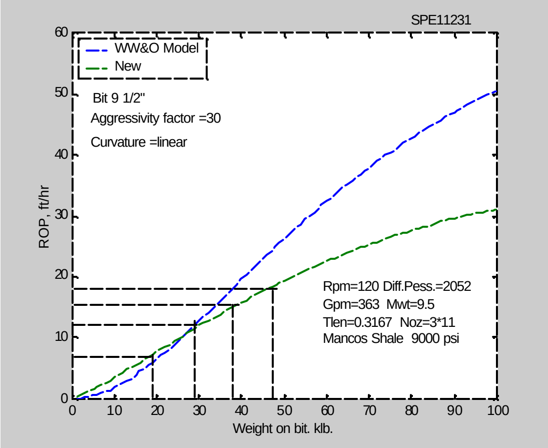


Figure 18

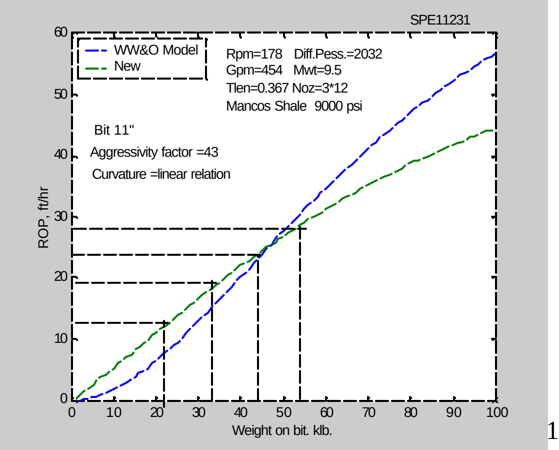


Figure 19

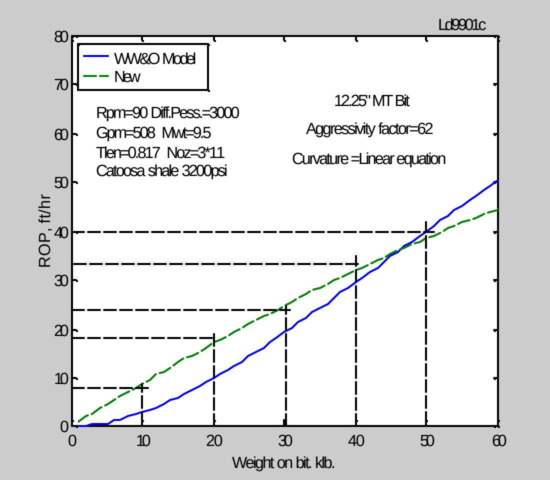


Figure 20