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(19)(CA) **APPLICATION FOR CANADIAN PATENT** (12)

(54) Method of Predicting Drill Bit Performance

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(57) 14 Claims

ABSTRACT OF THE DISCLOSURE

A method is disclosed for predicting the performance of a drill bit. By using a generalized model, with bit description, operating conditions and rock properties as inputs, the rate of penetration and duration for the bit can be predicted. Further, model is based on theoretical considerations of single-cutter rock interaction and can include a variable for cutter wear.

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"METHOD OF PREDICTING DRILL BIT PERFORMANCE"

Background of the Invention

1. Field of the Invention

The present invention relates to a method of predicting drill bit performance and, more particularly, to such a method that can predict the performance of different configurations of drill bits.

2. Setting of the Invention

Two classes of drill bits are normally used in the petroleum exploration industry: drag bits and roller-cone bits. Drag bits have gained in popularity in recent years because of their increased use with high speed downhole motors. Drag bits seem to have longer bit life, due to better cutter wear characteristics. Also, unlike roller-cone bits, they do not have bearings which fail easily and shorten bit life. To assist in selecting a bit to use in a particular location, the anticipated drilling performance of a bit is desired. One usually wants to know how fast a particular bit will penetrate a particular type of formation and how long will the bit

effectively penetrate before wearing out. Several articles that describe drag bit modeling are:

Appl, F. C. and Rowley, D. S., "Analysis of the Cutting Action of a Single Diamond," Soc. of Petr. Engrs. J. (September 1968), 269-280.

Peterson, J. L.: "Diamond Drilling Model Verified in Field and Laboratory Tests," Journal of Petr. Tech. (February 1976), 213-223.

Warren, T. M. and Sinor, L. A.: "Drag Bit Performance Modeling," SPE Paper No. 15618, Presented at SPE Annual Technical Conference and Exhibition, New Orleans, LA (October 1986).

The geometrical correlations were derived from Perry, R. H. and Chilton, C. H.: Chemical Engineers' Handbook, Fifth Edition, McGraw Hill, New York, NY (1973), Page 2-7.

Attempts to predict drilling performance for drag bits have been made by various investigators. Natural diamond bit predictive models were first developed by Appl and Rowley in 1968 and by Peterson in 1976. Appl and Rowley assumed a plastic Coulomb rock failure with Mohr circle failure criteria and the energy required to remove the rock was obtained from the mechanical energy applied to the bit. Peterson used a static loading condition and an equivalent blade concept, both of which are inapplicable to normal drilling situations. In fact,

Peterson's equivalent blade concept has been found to be impractical and difficult to adapt for natural diamond bits and other bits that do not have blades.

A polycrystalline diamond compact (PDC) performance model was developed by Warren and Sinor. The model is a weight-on-bit (WOB) model, i.e., the penetration rate is an input and WOB is the output. The model requires detailed descriptions of cutter geometry and cutter placement on the bit face. Therefore, it can be time consuming to run. The model is useful for detailed bit-design studies, such as single-cutter wear profile, bit balance and vibration, etc. Further, there are no known models that can accurately predict Geoset-type bits. There is a need for a simple, universal model that with few inputs can provide accurate and useful bit performance information.

Summary of the Invention

The present invention has been developed to overcome the foregoing deficiencies and meet the above described needs. Specifically, the present invention provides a method for predicting the drilling performance of a drill bit without the need for a detailed description of the bit such as the bit geometry and arrangements for the purposes of bit design, selection and operation. Lithology coefficients are used to describe the type of rock in which the modeled drill bit is to be evaluated, and selected optimal bit conditions, such as WOB and RPM are used to place boundaries on the modeling process. Once the above lithological coefficients are obtained, the rate

of penetration (ROP) and duration of a bit run can be calculated from the equation described hereinafter.

This invention describes a new approach to model mathematically the drilling performance of full-hole and core drag bits -- natural diamond bits (NDB), polycrystalline diamond compact bits (PDC), and Geoset bits. With this new method, the drilling performance of any drag bit, i.e., bits without rotating cones, whether new or worn, can be predicted given the bit description, operating conditions and rock properties.

The model can be used both for drilling preplanning and also for parametric studies to determine effects on penetration rate of bit and operating parameters. This optimization approach based on model sensitivity analysis has not been utilized for drag bit design and operation before. The model is based on theoretical considerations of single-cutter rock interaction, together with empirical calibration factors to account for considerations not amenable to theoretical treatment. Significant features incorporated in the model include "equivalent bit radius," "dynamic cutter action," and "lithology coefficients."

Brief Description of the Drawings

Figure 1a is a three part illustration of a natural diamond bit cutter geometry.

Figure 1b is a three part illustration of a Geoset bit cutter geometry.

Figure 1c is a three part illustration of a polycrystalline compact diamond (PDC) cutter geometry.

Figure 2 is an illustration with explanatory equations of the dynamic cutting action of a single cutter.

Figure 3 is an illustration with explanatory equations of the volume of rock material removed per cutter per revolution of a drill bit.

Figure 4 is a graphical representation of how penetration rate is not linearly dependent upon RPM.

Figure 5 is a graphical representation of penetration rate versus RPM for different weight on bit for the bit used in Figure 4.

Figure 6 is an illustration of a cutter's configurational changes because of wear.

Figure 7 is an illustration with explanatory equations of the volume of rock not removed due to cutter wear.

Figure 8 is a graphical representation and comparison between actual and calculated ROP versus RPM through shale for a bit.

Figure 9 is a graphical representation and comparison between actual and calculated ROP versus WOB through limestone for a bit.

Figure 10 is a graphical representation and comparison between actual and calculated ROP versus WOB through shale for a bit.

Figure 11 is a graphical representation and comparison between actual and calculated ROP versus WOB through shale for a bit.

Figure 12 is a graphical representation and comparison between actual and calculated ROP versus WOB through limestone for a worn bit.

Figure 13 is a graphical representation of the predicted model results sensitivity to changes in operating parameters.

Figure 14 is a graphical representation of the predicted model results sensitivity to changes in bit parameters.

Figure 15 is a graphical representation and comparison of the actual and calculated ROP for a bit without wear correction.

Figure 16 is a graphical representation and comparison of the actual and calculated ROP for a bit with wear correction.

Detailed Description of the Preferred Embodiments

The present invention provides a method of modeling any configuration of drill bit and from the model predicting the rate of penetration and duration for a given lithology and operating conditions. The present model is based on physical phenomena with empirical correction coefficients from lab and/or field data. The basic assumptions of the model are that for a particular group of drag bits, all cutters are roughly the same average geometry, and are equally loaded. significant concepts described below include (1) equivalent bit radius, (2) dynamic cutter loading, and (3) lithology coefficients.

Figure 1 shows three typical cutter geometries; one for natural diamond bits (1a), one for Geoset bits (1b) and one for polycrystalline compact diamond bits (1c). The following discussion concentrates on the natural diamond bit model, although, as shown later, it can be modified for other drag bit types.

The dynamic rock penetration criterion is used, i.e., the cutter projected (contact) area with the rock is half of Peterson's area (see Fig. 2). This represents dynamic (moving) cutting action as opposed to Peterson's static action. In general, the projected area is given by

$$A_p = \frac{W_{mech}}{\sigma_c} \qquad (1)$$

where A_p = projected (contact) area of each cutter,

σ_c = rock compressive strength, and

W_{mech} = mechanical loading per cutter diamond, i.e., applied weight-on-bit less the pump-off force, divided by the number of diamonds.

From basic geometry, the projected dynamic cutting area for a natural diamond type cutter given by

$$A_p = \frac{\pi}{2}\left[\frac{d_s^2}{2} - \left(\frac{d_s}{2} - p\right)^2\right] = \frac{\pi}{2}(d_s P - P^2) = \frac{\pi d_s P}{2}, \qquad (2)$$

assuming $d_s P >> P^2$, as will be generally applicable, where

d_s = diamond (stone) cutter diameter, and

P = diamond cutter penetration

Combining Equations 1 and 2 to eliminate A_p, the diamond penetration, P, is obtained such that

$$P = \frac{2W_{mech}}{\pi(d_s \sigma_c)} \quad . \qquad (3)$$

Using P again, an equation is obtained for A_v, the area being compressed in front of a cutter, as shown in Figure 3, such that

$$A_v = (\frac{d_s}{2})^2 \times \cos^{-1}(1-(2 \times P/d_s))-(d_s \times P-P^2)^{1/2}(d_s/2-P) \qquad (4)$$

To avoid complications associated with detailed description of each cutter location on the bit face, an assumption is made that all cutters can be visualized as located at an "equivalent radius" and thus each cutter does equal work, which is an average. Therefore, all cutters travel an effective distance $2\pi R_e$ per revolution. Equivalent radius, R_e is defined in Fig. 3 such that

$$A_1 = A_2 = \frac{1}{2} A_B \qquad (5)$$

where A_B is the bit-face area.

Areas A_1 and A_2 are defined such that they remove the same rock volume.

Mathematically, $2\pi R_e^2 = \pi R_B^2$, where R_B is the radius of the bit face, giving

$$R_e = R_B/\sqrt{2},$$

or (6)

$$R_e = D_B/(2\sqrt{2}) \text{ for full hole bits.}$$

For core bits, the applicable equation is

$$R_e = \frac{1}{2\sqrt{2}} \sqrt{(D_o^2 + D_i^2}\ , \qquad (7)$$

where D_o, D_i are outer and inner diameters of the core bit.

The same approach can be used to define applicable equivalent radius for bits with unusual cutter distributions or bit face profiles.

Summing the volume removed for all diamonds gives V_D = volume removed per revolution in the form

$$V_D = 2\pi R_e \cdot N_c \cdot A_v \qquad (8)$$

where N_c = number of cutters.

To obtain the rate of penetration (ROP) in ft/hr, the volume, V_D is divided by the bit face area, and appropriate units correction is applied. For full-hole bits,

$$ROP = 14.14\left(\frac{1}{D_B}\right)(N_c \cdot RPM \cdot A_v) \quad . \tag{9}$$

Substituting for A_v and P,

$$ROP = 14.14\left(\frac{N_c \cdot RPM}{D_B}\right)\left[\frac{d_s}{2}\cos^{-1}\left(1 - \frac{4W_{mech}}{N_c d_s^2 \pi \sigma_c}\right)\right. \tag{10}$$

$$\left. - \left(\frac{2W_{mech}}{N_c \pi \sigma_c} - \frac{4W_{mech}^2}{N_c^2 d_s^2 \pi \sigma_c^2}\right)^{1/2}\left(\frac{d_s}{2} - \frac{2W_{mech}}{N_c \pi \sigma_c d_s}\right)\right]$$

For core bits,

$$ROP = 14.14 \left(\frac{\sqrt{D_o^2 + D_i^2}}{(D_o^2 - D_i^2)}\right) \times (N_s \times RPM \times A_v) \tag{11}$$

D_i is bit inner diameter in the case of a core bit, and equals zero for full bits. D_o is the outer diameter. Notice that for $D_i = 0$, Equation 11 defaults to Equation 9 with $D_o = D_B$.

Experience from lab and field studies shows that the behavior of the bit penetrating the rock is not linearly dependent on RPM as ideally predicted by Equations 9 to 11. This is shown to be so in Figure 4. A correction factor, therefore, is introduced to model phenomena not modeled theoretically. Such phenomena cause deviations from theory and include effects such as rock strain rate and bit cleaning (hydraulics). At this time, these effects are not accounted for rigorously in the model as they are not amenable to accurate theoretical description. The mechanical weight-on-bit (WOB) empirical correction is also incorporated in the model depending on cutter geometry and lithology (see Figure 5).

The "lithology total correction factor," COR = $a/(RPM^b \times WOB^c)$, has the same set of a,b,c coefficients for each cutter geometry describing a particular drag-bit group (NDB, PDC, Geoset, etc.). These coefficients are developed from lab or field drill-off tests using non-linear regression analysis. The theoretical ROP from Equation 9-11 is then multiplied by the lithology coefficient, COR, to obtain the model prediction of ROP.

As an example, for natural diamond bits, only one set of a, b, c coefficients is needed to describe the performance for one lithology, because all cutters are assumed to be spherical. The same principle applies to Geoset and PDC bits. Although the present invention disclosure concentrates on diamond-bit modeling, equations developed for Geoset and PDC bits are included as part of the invention.

Other drag bits can be treated in the same manner. The projected area and the area in front of the cutter are calculated depending only on cutter geometry. Referring to Fig. 1c, for PDC bits

$$A_p = \mathrm{Sin}(\theta)\left[\left(\frac{d_c}{2}\right)^2 \cos^{-1}\left(1 - \frac{2P}{\cos(\theta)d_c}\right) - \left(\frac{d_c P}{\cos(\theta)} - \frac{P^2}{\cos^2(\theta)}\right)^{1/2}\left(\frac{d_c}{2}\,\frac{P}{\cos(\theta)}\right)\right] \quad (12)$$

$$A_v = \cos(\alpha)\cos(\theta)\left[\left(\frac{d_c}{2}\right)^2 \cos^{-1}\left(1 - \frac{2P}{\cos(\theta)d_c}\right) - \left(\frac{d_c P}{\cos(\theta)} - \frac{P^2}{\cos^2(\theta)}\right)^{1/2}\left(\frac{d_c}{2}\,\frac{P}{\cos(\theta)}\right)\right] \quad (13)$$

where

θ = cutter backrake angle

α = cutter siderake angle

d_c = diameter of cutter.

From Figure 1b, for Geoset bits,

$$A_p = 2 \times L \times \mathrm{Tan}(\theta) \times P \quad (14)$$

$$A_v = P^2 (\mathrm{Tan}(\theta)) \qquad (15)$$

where

θ = cutter included angle.

L = Geoset cutter length.

It should be noted that for Geoset cutters, siderake and backrake angles are easily introduced depending on the bit specifics. Also, it is possible that siderake and backrake angles may affect the a, b, c coefficients for both Geoset and PDC bits. However, such additional consideration does not appear to apply to natural diamond bits.

In order to support actual drilling operations including progressive bit wear, the rock uniaxial compressive strength, rock abrasiveness coefficient, the properties of the cutter compact material, as well as operating conditions are used in calculating the cutter volume removed by wear. As the cutter volume removed is calculated, the new penetration rate is modified accordingly based on the new projected area and rock volume removed per cutter. This concept is illustrated in Figure 6. As the cutter becomes worn, the following wear equation results:

$$V_D = \sum_{1}^{n} CA \times \frac{RPM}{R_e} \times \frac{WOB}{N_s} \times \sigma_c \times AB_R \,, \qquad (16)$$

... n refers to footage drilled.

where

CA = wear coefficient for the cutter

RPM/R_e = relative cutter velocity

WOB/N_s = Mechanical loading on each cutter

σ_c = uniaxial compressive strength of the rock

AB_R = relative abrasiveness of formation

The volume lost from the cutter is given in Figure 7, using Reference 4, as

$$V_D = \frac{\pi}{2}(P_w{}^2 d_s) \qquad (17)$$

where P_w is the cutter penetration lost due to wear. Transposing,

$$P_w = \sqrt{\frac{2 \times V_D}{\pi \times d_s}} \qquad (18)$$

The new projected area due to wear from Figure 6 is now given by

$$A_{pw} = \pi \left(\frac{\sqrt{d_s P_w}}{2}\right)^2 = \frac{\pi d_s P_w}{2} \qquad (19)$$

Total projected area with wear, A_p equals $A_{pold} + A_{pw}$ (see Figure 6). Mathematically,

$$A_p = \frac{\pi d_s P_1}{2} + \frac{\pi d_s P_w}{2} \qquad (20)$$

where P_1 is the diamond penetration with wear (i.e., $P_1 = P - P_w$)

$$P_1 = \frac{2A_p}{\pi d_s} - P_w \qquad (21)$$

Similarly, the new area involved in the rock volume removal is given by

$$A_{v1} = A_v - A_{vw} \qquad (22)$$

where

$$A_{vw} = \left(\frac{d_s}{2}\right)^2 \times \cos^{-1}\left(1 - \left(2 \times \frac{P_w}{d_s}\right)\right) - \left((d_s \times P_w - P_w^2)^{1/2} \times (d_s/2 - P_w)\right) \qquad (23)$$

The new A_v is given by

$$A_{vl} = \left(\frac{d_s}{2}\right)^2 \times \cos^{-1}\left(1 - \left(2 \times \frac{P}{d_s}\right)\right) - \left(d_s \times P - P^2\right)^{1/2} \times \left(d_s/2 - P\right) - A_{vw} \quad (24)$$

This is then input into the equation for volume removed per revolution, and a new ROP is calculated to include cutter wear. The same procedure can be followed for PDC and Geoset bits. The difference again lies in the cutter geometry. Also, for Geoset and PDC cutters, wear coefficient, CA, is obtained from the following equation

$$CA = f(D_m) = C'(D_m) \quad (25)$$

where C' = is a constant describing D_m, and

D_m = is micron size of diamond inside the polycrystalline compacts.

The volume of cutter removed, V_D, is found from the equations describing the cutter geometry. The penetration rate is then back calculated for the cutter the same way as for natural diamond bits described earlier. The projected area increases, decreasing the effective stress, and the area removing the rock volume decreases resulting in decreased ROP. This also means that because of the wear-flat, an initial WOB is required before the rock is penetrated. Viewed in another sense, the model

provides a tool to predict how worn the diamonds are by performing WOB drill-off tests.

Using this wear model, one can predict how the bits will wear every foot while drilling different formations under different operating conditions. The most effective bit can then be selected based on economics.

EXAMPLE APPLICATION

The model can give ROP predictions for different lithologies and rock strengths (uniaxial compressive strength). This provides the capability of predicting penetration rate for any set of operating conditions, formation description and bit parameters. As an example, drill-off data from a 6-1/4" natural diamond bit were used to determine applicable a, b, c coefficients. This set of coefficients was then applied to OTHER natural diamond bits with DIFFERENT design features. Refer to Table 1. The bits that were evaluated are listed in Table 2. Typical results shown in Figures 8-11 indicate good match between the present model and field data. Note that Figure 12 applies to a worn bit. The model, therefore, overpredicts the bit performance in this case, as expected.

Parametric evaluations of operating variables and bit design features can be done as shown in Figures 13 and 14. These figures show that the model can be used to study effects on ROP of changes in bit parameters and operating conditions. Given a set of conditions in the field, the

model can be used to study parameters that would optimize ROP. For example, Figure 13 shows that if other parameters are held constant, increase in applied weight-on-bit will increase the ROP significantly. On the other hand, the mud weight does not show a high degree of sensitivity. The same conclusions can be drawn for bit parameters, such as bit diameter, diamond size, etc., shown in Figure 14. This application could be used to impact actual bit design to optimize the rate of penetration.

Figures 15 and 16 show the Geoset bit match between actual field data and model prediction without wear and including wear. Data from the first 50 ft of the well were used to generate the a, b, c coefficients. The corrected model was then used to predict drilling performance before the rest of the hole was drilled. The match with no wear correction is poor (Figure 15). However, with wear correction (Figure 16), the actual field data match the model predictions very well. The unmatched section at 4550 ft is due to a change in lithology from that used to develop the a, b, c lithology coefficients.

The new mathematical model described herein has been programmed on the computer and has been used as follows:

1. To optimize the operating parameters and bit selections and obtain the maximum ROP and minimum $/ft. The bit runs can be simulated before actually drilling the well and, therefore, can form an important part of overall well planning strategy.

2. From Figures 13 and 14, the model can be used for parametric studies. The model has the capability to optimize bit design features by evaluating different bit parameters and their effects on ROP and $/ft. The most suitable bit design for a particular situation can then be selected.

3. The model can be used to support total drilling system studies for penetration-rate, solids-control and hydraulics optimization. Economic impacts of the model can range in the thousands of dollars for one well, depending on operating conditions and expenses.

Major advantages of the new model are

1. The model is uncomplicated and straight forward.

2. Data requirements are standard, readily-available bit and drilling data.

3. Prediction for natural diamond bits have shown good agreement with lab and field data.

4. The model runs fast and is excellent for a drilling simulator, or as a stand-alone model.

5. Although at this time tested for natural diamond bits, the model can be generalized for other types of

drag bits by incorporating the appropriate cutter geometric description in the model.

Whereby the present invention described in relation of the examples and drawings attached hereto; however, it should be understood that other and further modifications, apart from those shown or suggested herein, may be made within the scope and spirit of the present invention.

What is Claimed is:

1. A method of predicting the rate of penetration for a drill bit comprising:

(a) determining for the drill bit a selected operating condition comprising revolutions per minute (RPM), weight on bit (WOB), and compressive strength of the material through which the drill bit is to drill;

(b) determining a geometry of the drill bit comprising drill bit diameter, number of cutters, face area, cutter dimensions, and equivalent cutter radius,

(c) from the inputs of steps (a) and (b), determining the dynamic cutting area for the cutters; and

(d) from the inputs of steps (a), (b) and (c), determining the volume of material removed with each revolution (V_D) divided by face area of the drill bit (D_B) to generate a predicted rate of penetration (ROP).

2. The method of Claim 1 wherein the equivalent cutter radius is calculated from an equation equivalent to:

$$R_e = D_B / (2 \sqrt{2})$$

wherein D_B is the drill bit diameter for the full hole bits.

3. The method of Claim 1 wherein the equivalent cutter radius is calculated from an equation equivalent to:

$$R_e = (1 / (2 \sqrt{2})) / (D_o^2 + D_i^2)^{1/2}$$

wherein D_o is the outer drill bit diameter and D_i is the inner drill bit diameter.

4. The method of Claim 1 wherein the dynamic cutting area for the cutter is calculated from an equation equivalent to: $Area_p = (\pi d_s P)/2$ wherein d_s is the cutter diameter and P is cutter penetration.

5. The method of Claim 4 wherein the cutter penetration is determined from an equation equivalent to: $P = 2 W_m / \pi (d_s \sigma_c)$ wherein W_m is the weight on bit less a pump-off force divided by the number of cutters, d_s is the cutter diameter and σ_c is the rock compressive strength.

6. The method of Claim 1 wherein ROP is calculated from an equation equivalent to:

$$ROP = 14{,}14 \left(\frac{N_c \cdot RPM}{D_B}\right) \left[\frac{ds}{2} \cdot \cos^{-1}\left(1 - \frac{4 W_m}{N_c d_s^2 \pi \sigma_c}\right) - \left(\frac{2 W_m}{N_c \pi \sigma_c} - \frac{4 W^2 m}{N_c d_s^2 \pi \sigma^2 c}\right)^{1/2} \cdot \left(\frac{ds}{2} - \frac{2 W_m}{N_c \pi \sigma_c d_s}\right)\right]$$

wherein Nc = number of cutters

RPM = revolutions per minute

DB = drill bit diameter

ds = cutter diameter

Wm = mechanical loading per cutter

σc = rock compressive strength

7. The method of Claim 1 wherein the ROP determined in step (d) is multiplied by a lithology total correction factor (COR).

8. The method of Claim 7 wherein the COR is calculated using an equation equivalent to: $COR = a/(RPM^b \cdot WOB^c)$ wherein constants a, b and c are lithology corrections dependent on cutter geometry and calculated from nonlinear regression analysis.

9. The method of Claim 1 wherein the cutter dimensions for polycrystalline diamond cutters include cutter backrake angle, cutter siderake angle and cutter diameter.

10. The method of Claim 1 wherein the cutter dimensions for Geoset-type cutters include cutter included angle and Geoset cutter length.

11. The method of Claim 1 wherein the calculation of the volume of material removed with each revolution (V_D) includes a depth dependent wear factor.

12. The method of Claim 11 wherein the wear factor is calculated from a wear coefficient for the cutters, relative cutter velocity and relative abrasiveness of the rock.

13. The method of Claim 12 wherein the volume of material removed (V_D) with depth dependent wear factor is calculated utilizing an equation equivalent to:

$$V_D = \sum_{i}^{n} CA \cdot \frac{RPM}{R_e} \cdot \frac{WOB}{N_c} \cdot AB_R \cdot \sigma_c$$

wherein

i, ... n = the footage drilled,

CA = wear coefficient for the cutters,

RPM/R_e = relative cutter velocity,

WOB/N_c = mechanical loading on each cutter,

σ_c = uniaxial rock compressive strength, and

AB_R = relative abrasiveness of rock.

14. The method of Claim 13 wherein the wear coefficient for cutters (CA) for polycrystalline diamond cutters (PDC) and Geoset-type cutters is calculated from an equation equivalent to:

$$CA = C' (D_m)$$

wherein C' = wear constant describing D_m, and

D_m = micron size of diamond within cutter.

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CUTTER GEOMETRY

DIAMOND BIT CUTTER

Daimond Cutter Travel →

FIG, 1A

GEOSET BIT CUTTER

Geoset Cutter Travel →

FIG. 1B

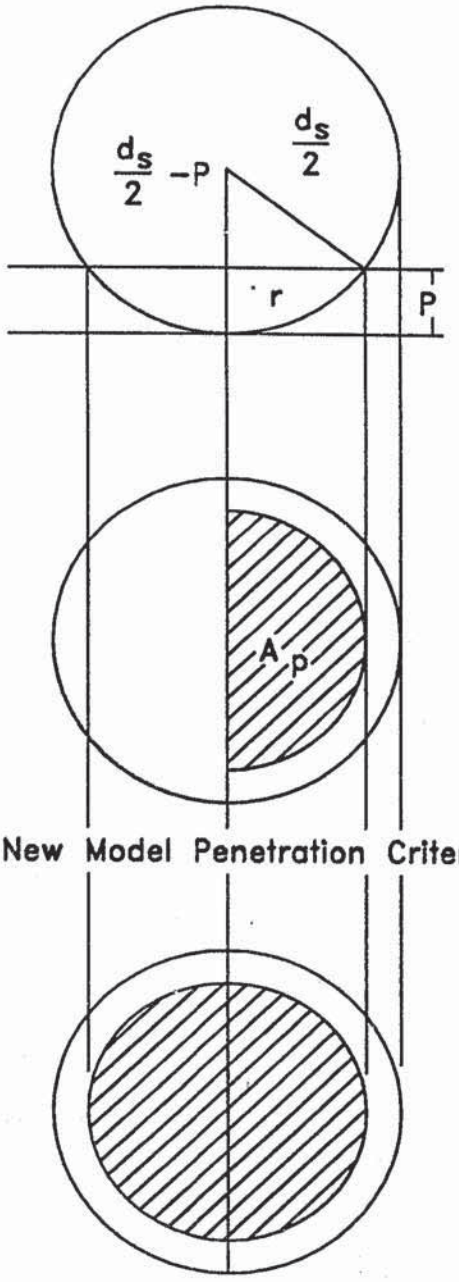
PDC BIT CUTTER

PDC Cutter Travel →

FIG. 1C

Gowling, Strathy & Henderson

SINGLE DIAMOND PENETRATION



New Model Penetration Criterion

$$r = \sqrt{\left(\frac{d_s}{2}\right)^2 - \left(\frac{d_s}{2} - P\right)^2}$$

$$r = \sqrt{d_s P - P^2}$$

$$A_p = \frac{\pi r^2}{2} = \text{Projected Contact Area}$$

$$= \frac{\pi}{2}\left(d_s P - P^2\right)$$

Loading Per Diamond:

$$WOB_{mech} = W_{Dia} \cdot N_{Dia}$$

Rock Failure Criterion:

$$\sigma_c = \frac{W_{Dia}}{A_p} = \frac{2W_{Mech}}{N_s \pi \left(d_s P - P^2\right)}$$

Assume $d_s P >> P^2$:

$$P = 2W_{Mech} / (N_s d_s \pi \sigma_c)$$

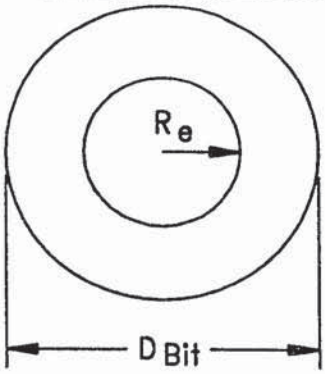
Peterson's Penetration Criterion

FIG. 2

Gowling, Strathy & Henderson

RATE OF PENETRATION CALCULATED FROM VOLUME REMOVED PER DIAMOND

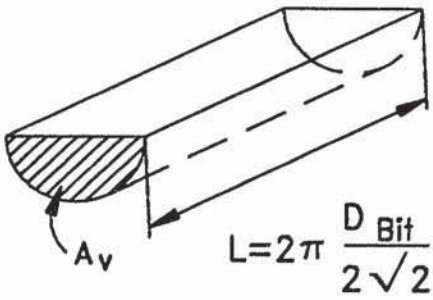
- Definition of Equivalent Radius:

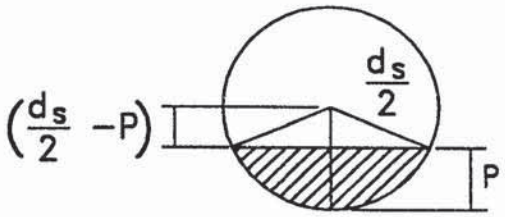


$$\pi R_e^2 = (D_{Bit}/2)^2 (1/2)$$

$$R_e = \frac{D_{Bit}}{2\sqrt{2}}$$

- Volume Removed per Diamond per Revolution:





$$A_v = \left(\frac{d_s}{2}\right)^2 \cos^{-1}\left(1 - \frac{2P}{d_s}\right) - 2x\frac{1}{2}\left(d_s P - P^2\right)^{1/2}\left(\frac{d_s}{2} - P\right)$$

$$V_{Dia} = 2\pi\left(\frac{D_{Bit}}{2\sqrt{2}}\right)\left[\left(\frac{d_s}{2}\right)^2 \cos^{-1}\left(1 - \frac{2P}{d_s}\right) - \left(d_s P - P^2\right)^{1/2}\left(\frac{d_s}{2} - P\right)\right]$$

- ROP (ft/hr) $= 14.14\left(\frac{N_s \cdot RPM}{D_{Bit}}\right)\left[\left(\frac{d_s}{2}\right)^2 \mathrm{Cos}^{-1}\left(1 - \frac{4W_{mech}}{N_s d_s^2\, \Pi\sigma_c}\right)\right.$

$$\left. - \left(\frac{2W_{mech}}{N_s\, \Pi\sigma_c} - \frac{4W_{mech}^2}{N_s^2 d_s^2 \Pi^2 \sigma_c^2}\right)^{1/2}\left(\frac{d_s}{2} - \frac{2W_{mech}}{N_s \Pi\sigma_c\, d_s}\right)\right]$$

FIG. 3

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6 1/4 D 331EB
RPM PERFORMANCE-CARTHAGE/SHALE
18 KLBS, RSCRN

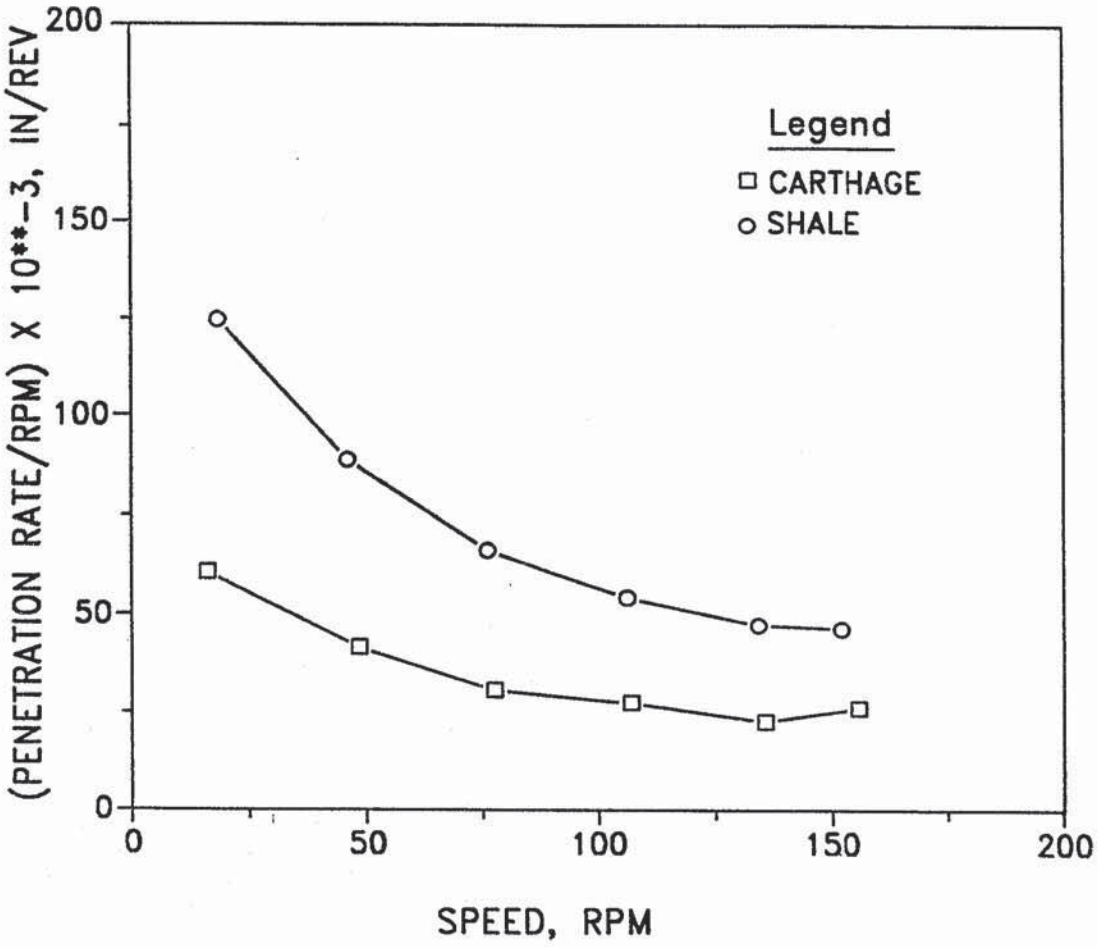

FIG. 4

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6 1/4 D 331EB
RPM PERFORMANCE–CARTHAGE, RWOBRN

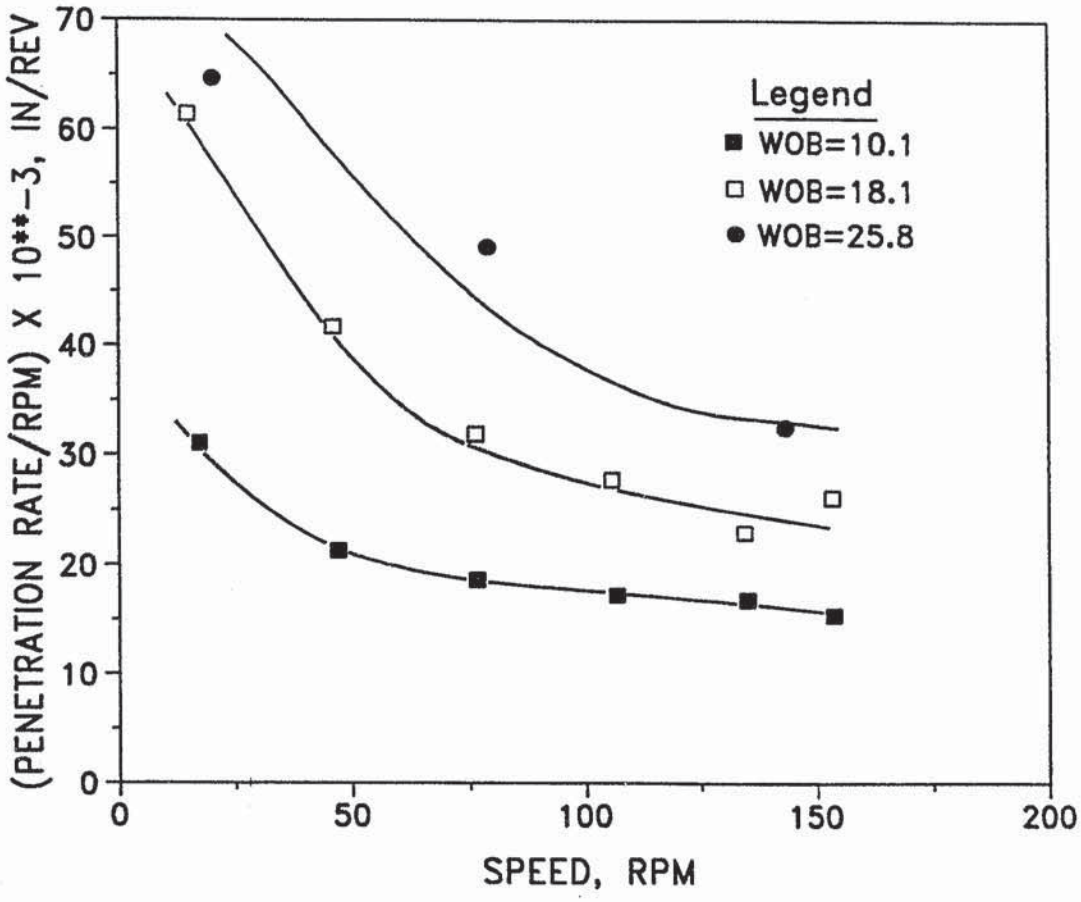

FIG. 5

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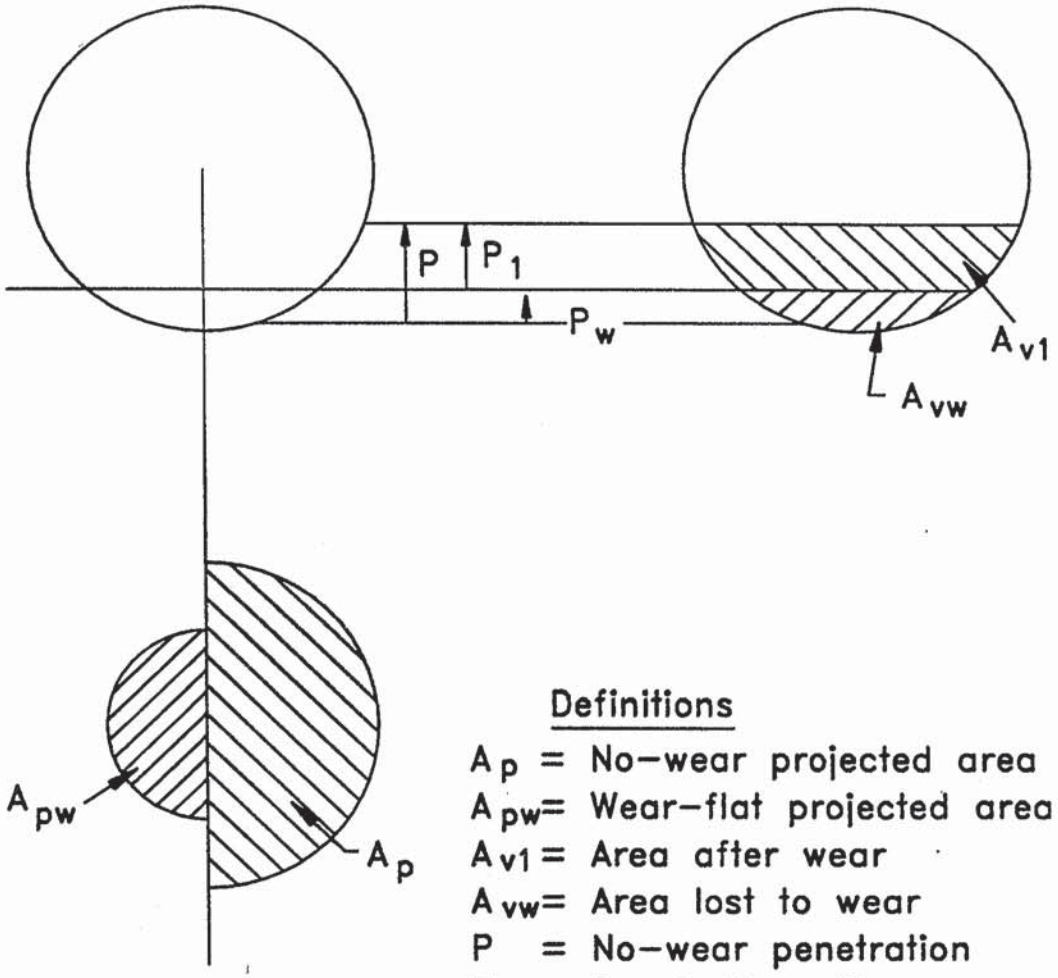
DIAMOND-WEAR ILLUSTRATION



Definitions

A_p = No-wear projected area
A_{pw} = Wear-flat projected area
A_{v1} = Area after wear
A_{vw} = Area lost to wear
P = No-wear penetration
P_1 = Penetration after wear
P_w = Penetration lost to wear

FIG. 6

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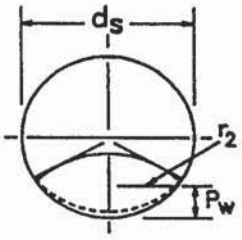
DIAMOND–WEAR CALCULATION

As the cutter wears, we have the following wear equation.

$$V_D = \sum_{i=1}^{n} CA \times \frac{RPM_i}{R_e} \times \frac{WOB_i}{N_s} \times \sigma_i \times AB_{R\,i}\,,\ i=1 \ldots n \text{ is per foot drilled.}$$

where:

V_D = volume of cutter removed
CA = wear coefficient for the cutter
RPM/R_e = relative cutter velocity
R_e = equivalent radius for the bit
WOB/N_{stress} = Mechanical loading on each cutter
σ = rock unixial compressive strength
AB_R = relative abrasiveness of formation



The volume lost from the cutter is given by[4]

$\frac{1}{6}\ \Pi P_w\ \left(3r_2^2 + P_w^2\right)$, where $r_2^2 = d_s\ P_w - P_w^2$

Substituting and simplifying, $V_D = \frac{\Pi}{2}\left(P_w{}^2 d_s\right)$,

where: $2P_w$ is assumed to be small compared to $3d_s$

where: P_w is the penetration loss due to wear

$$P_w = \left(\frac{2V_D}{\Pi d_s}\right)^{1/2}$$

FIG.7

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6 1/4 D 331EB
MODEL PREDICTION – SHALE

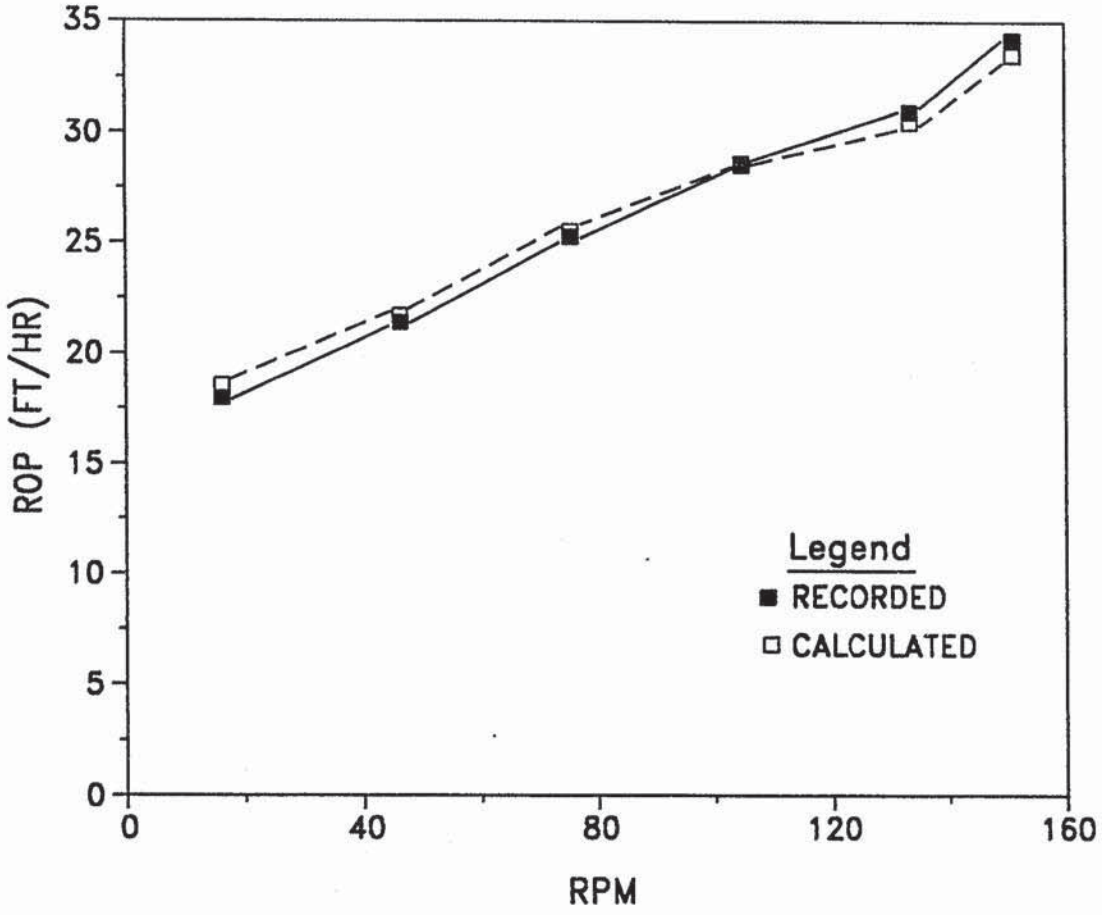

FIG. 8

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B112R536 PRIM-CARTHAGE LIMESTONE MWOB PERFORMANCE; RPM=99 BIT DM420; DIAM=8.5 GPM=346; MW=9.07; POB=1383

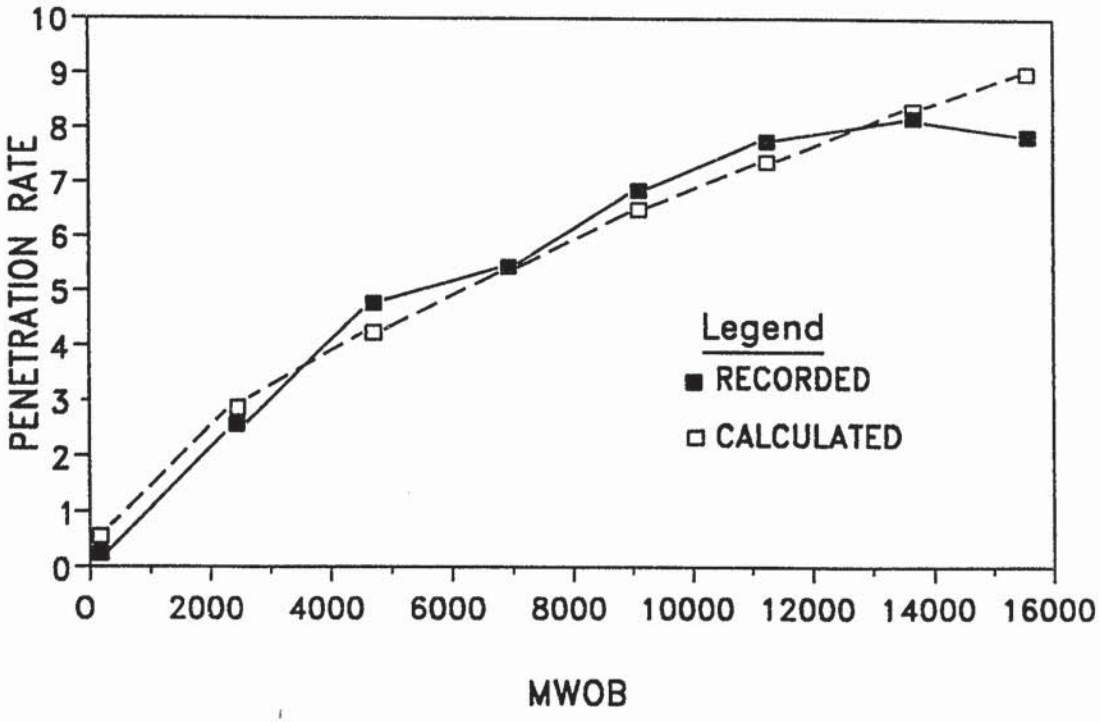

FIG. 9

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B112R477 PRIM-SHALE
MWOB PERFORMANCE; RPM=98
BIT DM610; DIAM=8.5
GPM=354; MW=9.30

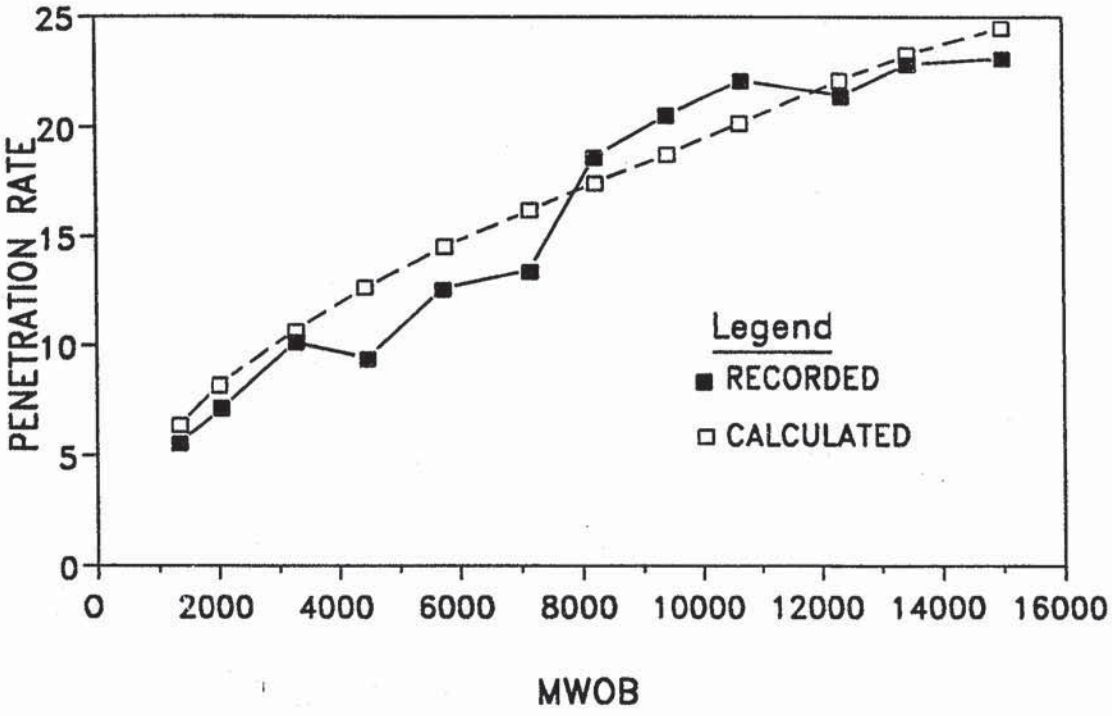

FIG. 10

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B112R417 PRIM-SHALE
MWOB PERFORMANCE; RPM=118
BIT DM910; DIAM=8.5
GPM=307; MW=9.33

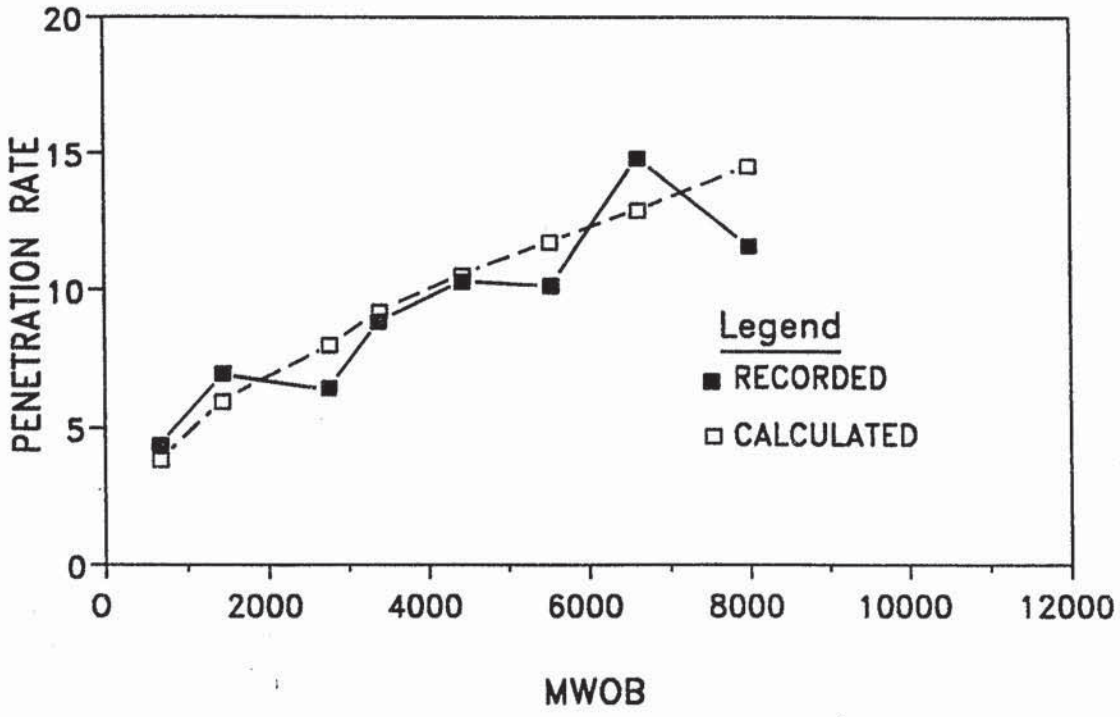

FIG. 11

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WORN-BIT STUDY
B112R322 PRIM-CARTHAGE LIMESTONE
MWOB PERFORMANCE; RPM=75
BIT D331EB; DIAM=8.5
GPM=393; MW=9.5

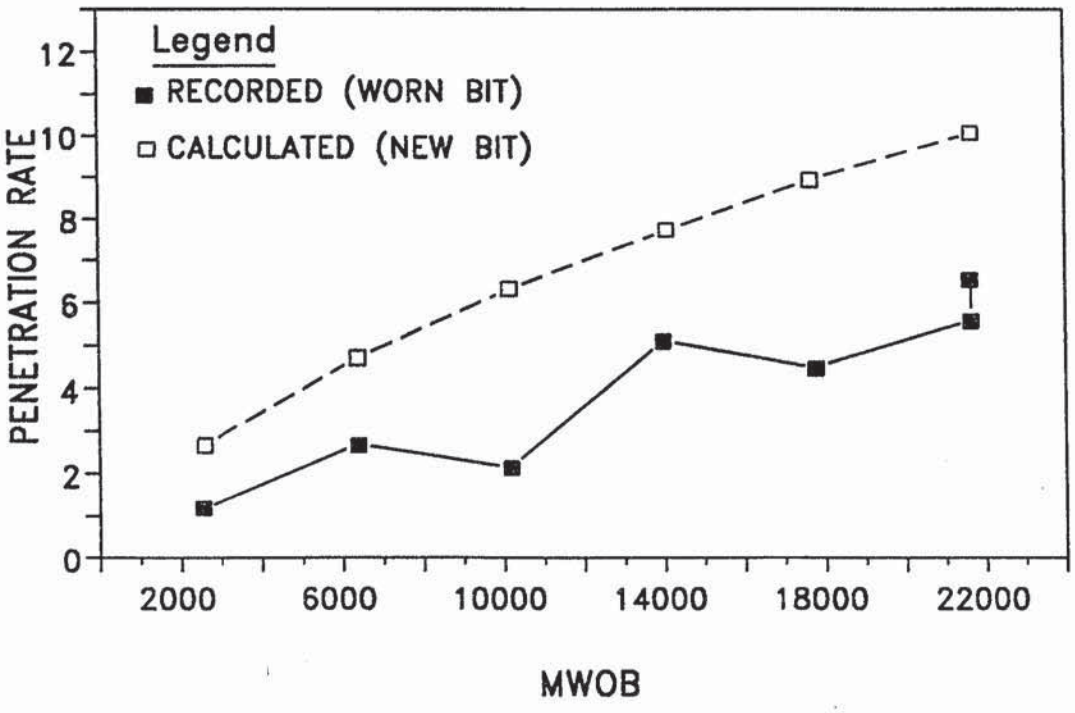

FIG. 12

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SENSITIVITY OF OPERATING PARAMETERS

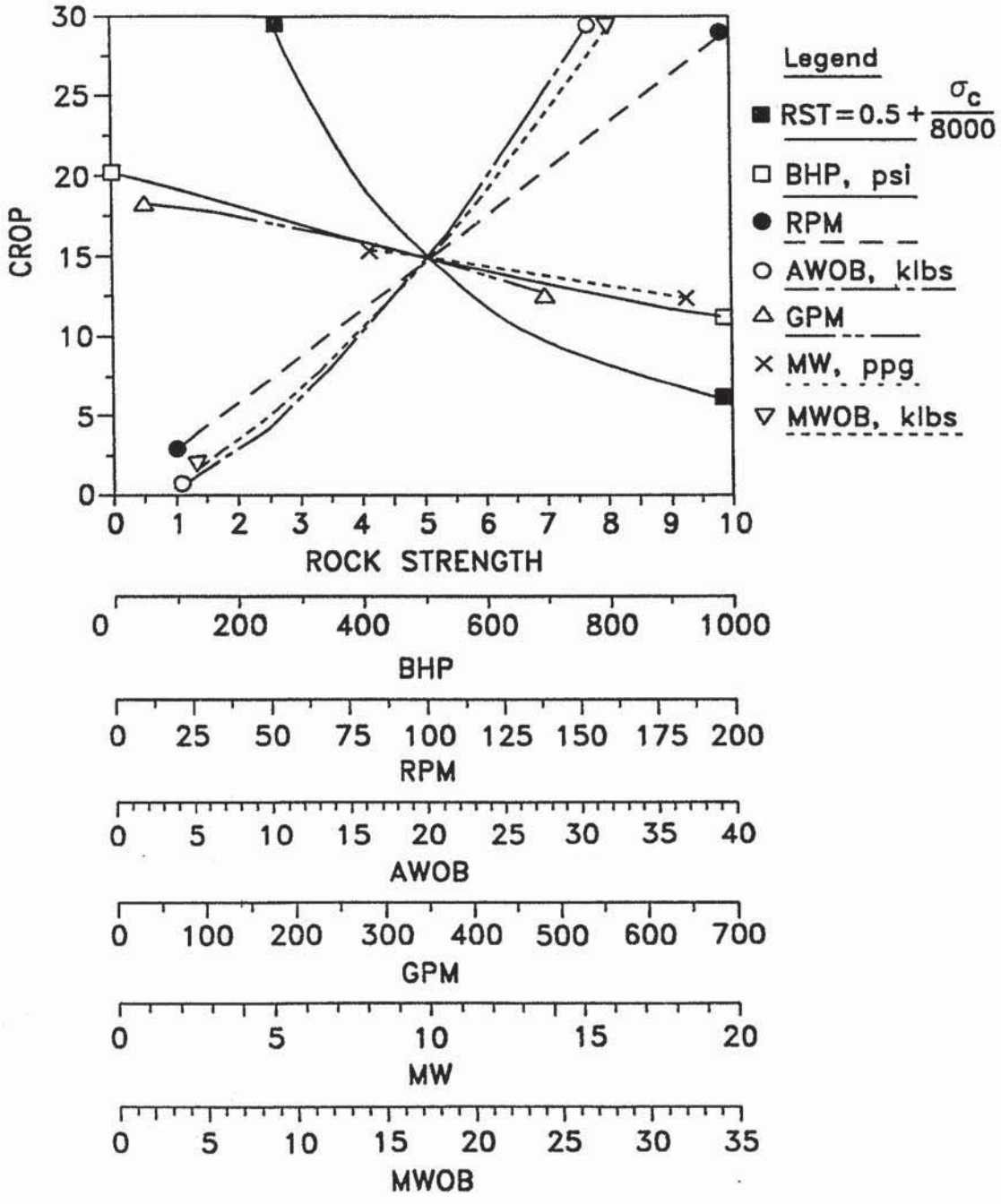

FIG.13

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SENSITIVITY OF BIT PARAMETERS

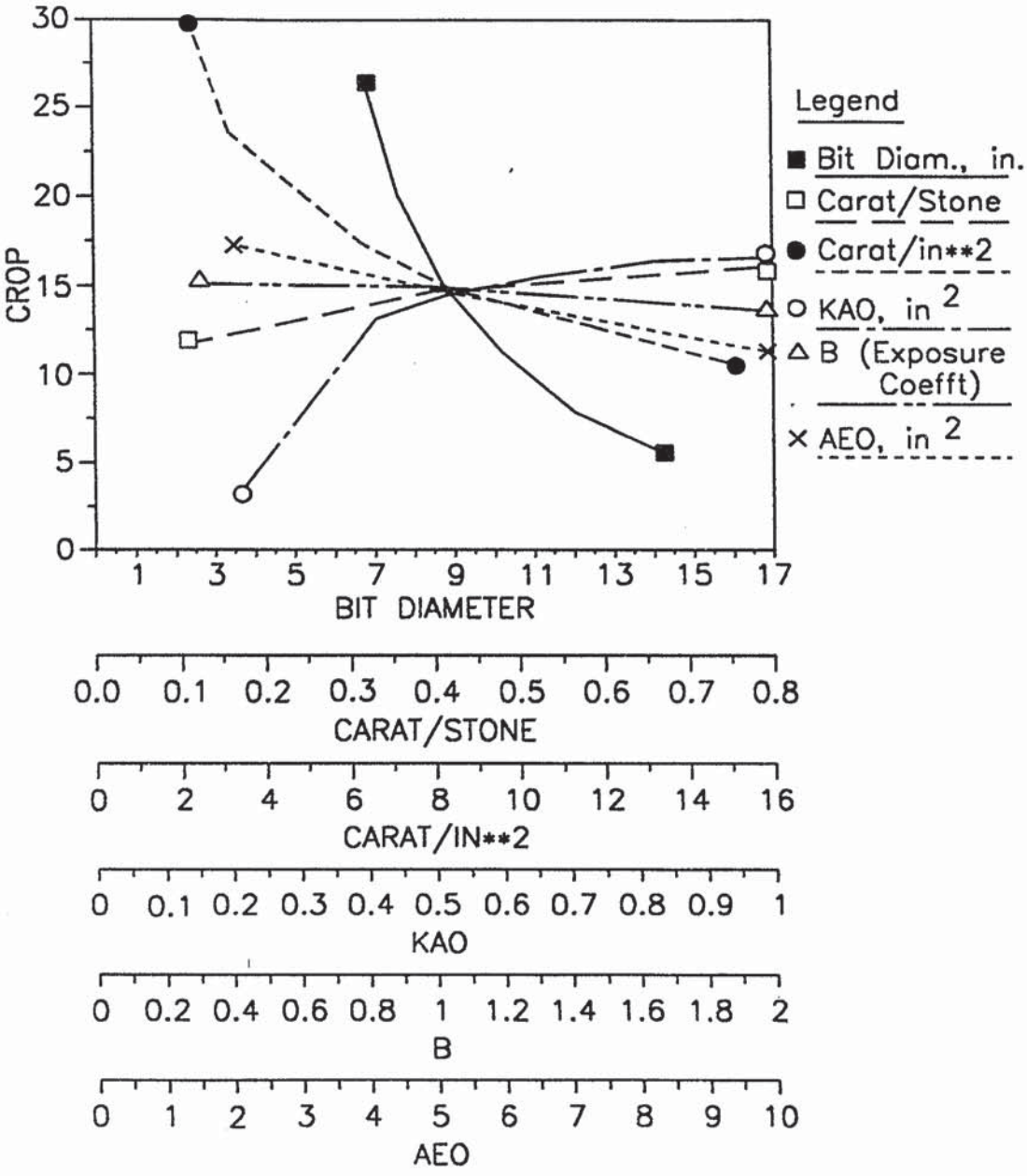

FIG.14

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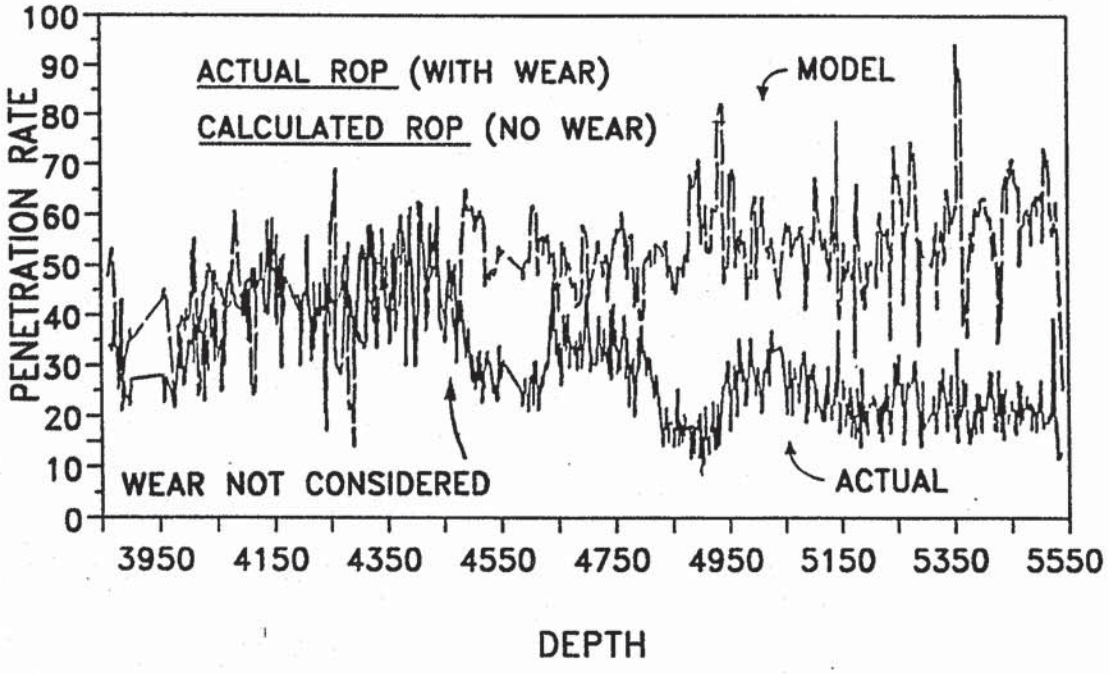

FIG. 15

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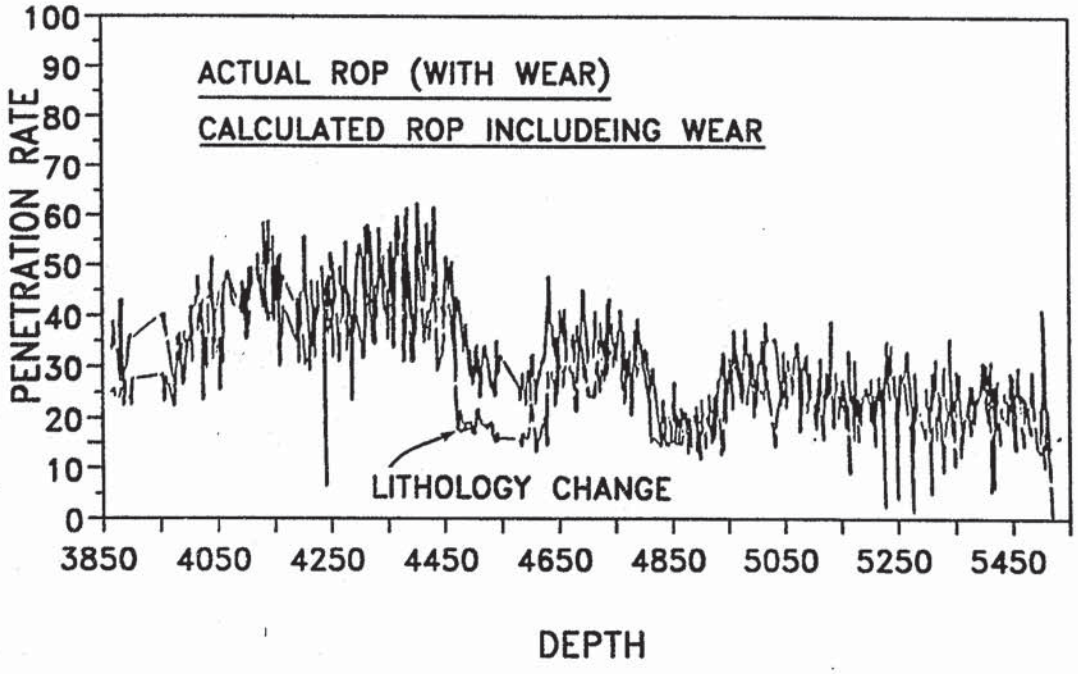

FIG. 16

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