

1 **METHOD FOR PREDICTING RATE OF PENETRATION USING BIT-**
2 **SPECIFIC COEFFICIENTS OF SLIDING FRICTION AND MECHANICAL**
3 **EFFICIENCY AS A FUNCTION OF CONFINED COMPRESSIVE STRENGTH**
4

5
6 **CROSS-REFERENCE TO RELATED APPLICATION**
7

8 This application hereby incorporates by reference U.S. Patent Application
9 entitled "Method for Estimating Confined Compressive Strength for Rock
10 Formations Utilizing Skempton Theory" by William Malcolm Calhoun and
11 Russell Thomas Ewy, filed concurrently with the present application.
12

13 **FIELD OF THE INVENTION**
14

15 The present invention relates generally to the drilling of well bores in
16 subterranean formations, and more particularly, to methods for predicting and
17 optimizing the rate at which the well bores are drilled including the proper
18 selection of drill bits and bit performance assessment.
19

20 **BACKGROUND OF THE INVENTION**
21

22 It has become standard practice to plan wells and analyze bit performance by
23 using log-based rock strength analysis and/or specific energy theory. The most
24 widely used characterization of rock strength is unconfined compressive
25 strength (UCS), but this is somewhat problematic because the apparent
26 strength of the rock to the bit is typically different than UCS. Specific energy
27 theory has been used for bit performance assessment for years. One of the
28 challenges of application of the specific energy theory, however, is uncertainty
29 or lack of consistency in reasonable values for input variables to be used in
30 specific energy based equations.
31

1 The present invention addresses the need to provide reasonable values for the
2 input variables used to predict rate of penetration and reactive torque of a drill
3 bit using specific energy theory

4 SUMMARY OF THE INVENTION

5
6 A method for predicting the rate of penetration (ROP) of a drill bit drilling a well
7 bore through intervals of rock of a subterranean formation is provided. The
8 method uses an equation based upon specific energy principles. For a drill bit,
9 relationships are determined between confined compressive strength CCS and
10 (1) a bit-specific coefficient of sliding friction, (2) mechanical efficiency EFF_M ,
11 (3) weight on bit WOB, and (4) bit rpm N. These relationships are determined
12 over a range of confined compressive strengths CCS and for a number of
13 predominant bit types. The confined compressive strength CCS is estimated
14 for intervals of rock through which the drill bit is to be used to drill a well bore.
15 The rate of penetration ROP and bit torque is then preferably calculated
16 utilizing the estimates of confined compressive strength CCS of the intervals of
17 rock to be drilled and bit type as the only inputs. Alternatively, ROP and bit
18 torque can be calculated utilizing one or more of the input
19 coefficients/parameters appropriately determined by another equally suitable
20 method or specified as a constant, and the estimates of confined compressive
21 strength and bit type as the only inputs for coefficients/parameters not
22 determined by another method or specified as constant.

23
24 Correction factors may also be determined for the effect that mud weight and
25 bit configuration have on those relationships between the coefficient of sliding
26 friction μ and mechanical efficiency EFF_M and the estimated CCS values.

27
28 The present invention establishes relationships for specific types of drill bits for
29 bit-specific coefficients of sliding friction μ and mechanical efficiency EFF_M , and
30 preferably weight on bit WOB and rpm N all as a function of apparent rock
31 strength and drilling environment (mud weight, equivalent circulating density
32 (ECD) etc.), and then uses these relationships to predict reasonable and

1 achievable ROP and associated bit torque based upon the apparent strength of
2 the rock which is to be drilled.

3

4 **BRIEF DESCRIPTION OF THE DRAWINGS**

5

6 These and other objects, features and advantages of the present invention will
7 become better understood with regard to the following description, pending
8 claims and accompanying drawings where:

9

10 FIG. 1 is a flowchart of steps used in a preferred embodiment of the present
11 invention to predict rate of penetration ROP for a drill bit drilling through
12 intervals of rock of a subterranean formation;

13

14 FIGS. 2A and 2B are flowcharts for determining bit-specific relationships for
15 input variables used in calculating ROP in FIG. 1, the relationships being
16 determined based upon simulator testing or expert based knowledge;

17

18 FIG. 3 is a schematic drawing of a well bore and confining fluid pressures
19 applied to rock in a depth of cut zone during drilling of rock by a drill bit;

20

21 FIG. 4 is a graph of differential pressure applied to rock in the depth of cut zone
22 versus radial position at the bottom of a hole for impermeable rock using
23 calculated values of confined compressive strength CCS and values of CSS
24 determined using a finite element model;

25

26 FIG. 5 is a chart produced during a full-scale simulator test for a roller insert bit
27 for hard formations;

28

29 FIG. 6 is a graph of a bit-specific coefficient of sliding friction μ as a function of
30 CCS for PDC bits with more than seven blades;

31

1 FIG. 7 is a graph of minimum and maximum mechanical efficiencies EFF_M as a
2 function of CCS for PDC bits with more than seven blades;

3

4 FIG. 8 is a graph of weight on bit WOB and WOB factor (lbs per inch bit
5 diameter) versus CCS for an 8.5" steel tooth bit type;

6

7 FIG. 9 is a graph of rotary drill speed N (RPM) versus CCS for roller cone bits;

8

9 FIG. 10 is a graph of a correction factor for coefficient of sliding friction μ versus
10 mud weight for PDC bits;

11

12 FIG. 11 is a graph of a correction factor for mechanical efficiency EFF_M versus
13 mud weight for PDC bits;

14

15 FIG. 12 is a graph of a correction factor for coefficients of sliding friction μ
16 which is dependent upon cutter size for PDC bits;

17

18 FIG. 13 is chart of a bit optimization and selection for a first well;

19

20 FIG. 14 is chart of a bit optimization and selection for a second well;

21

22 FIG. 15 is chart of a bit optimization and selection for a third well; and

23

24 FIG. 16 is chart of a bit optimization and selection for a fourth well.

25

26 **DETAILED DESCRIPTION OF THE INVENTION**

27

28 **I. Overview**

29

30 FIG. 1 illustrates a flowchart of steps taken in a preferred embodiment of the
31 present invention for calculating the rate of penetration (ROP) by a particular
32 type of drill bit into a subterranean formation under specified drilling conditions.

1 Details of these steps will be described in greater detail below. The rate of
 2 penetration ROP for the well bore is preferably estimated using specific energy
 3 theory. More particularly, equation (1) ideally is used to calculate the ROP as
 4 follows:

$$5 \quad ROP = \frac{13.33\mu N}{DB \left(\frac{CCS}{EFF_M * WOB} - \frac{1}{A_B} \right)} \quad (1)$$

6 where: ROP = Rate of penetration by a bit (ft/hr);
 7 μ = bit-specific coefficient of sliding friction;
 8 N = rotational speed of drill bit (revolutions per minute
 9 (RPM));
 10 D_B = diameter of bit (inches);
 11 CCS = confined compressive strength (apparent
 12 strength of the rock to the bit (psi));
 13 EFF_M = mechanical efficiency of the bit (percent);
 14 WOB = weight on bit (pounds); and
 15 A_B = area of bit (square inches).
 16

17 Referring now to the flowchart of FIG. 1, rock properties of the subterranean
 18 region to be drilled is determined in step 10. In particular, properties are
 19 determined such as unconfined compressive rock strength (UCS) and friction
 20 angle (FA) for intervals of rock to be drilled. Core samples from nearby well
 21 bores may be obtained and analyzed to determine properties of the rock which
 22 are likely to be encountered during the drilling of a well bore. Alternatively, by
 23 way of example and not limitation, such properties could be estimated from
 24 open hole logs or from seismic surveys. Next in step 15, properties such as in
 25 situ pore pressure PP of the rock, mud weights MW likely to be used during the
 26 drilling operation and overburden (OB) pressure for a given depth of formation
 27 are calculated. From these properties, the apparent rock strength (confined
 28 compressive strength CCS) for intervals of rock along the well bore path is
 29 determined in step 20.

30

1 Knowing the calculated CCS for an interval of rock, input values for μ , EFF_M , N ,
2 and WOB can be rapidly obtained from relationships which have previously
3 been determined such as by simulator testing or using expert based
4 knowledge. FIGS. 2A and B illustrate the source of how these relationships are
5 established. Bit characteristics such area of bit A_B and diameter of bit D_B are
6 known based upon the particular bit size for which the ROP calculation is to be
7 performed.

8
9 Values for these input variables may be modified in appropriate cases. For
10 example, correction factors for CF_{MW} may be applied in step 30 to EFF_M and μ
11 if the mud weight to be used for drilling is different from that mud weight under
12 which the relationship between EFF_M and μ and CCS were determined.
13 Likewise, a correction factor CF_{CS} may be applied in step 35 to μ if the cutter
14 size of a PCD bit is different from a PCD bit which was used to develop the μ
15 vs. CCS relationship.

16
17 In step, 40 the aforementioned inputs can be used to calculate the ROP of the
18 drill bit utilizing equation (1). Preferably, these inputs are known based upon
19 the CSS of the particular interval of rock being drilled and the drill bit
20 configuration.

21
22 Referring now to FIG. 2A, in order to determine the coefficients of sliding
23 friction μ and the mechanical efficiencies EFF_M for each particular type of drill
24 bit, full scale simulators tests using hydrodynamic pressures that are typically
25 encountered under normal drilling conditions are performed in step 50. Test
26 results from these full scale simulator tests are used in steps 55 and 60 to
27 establish relationships of bit-specific coefficients of sliding friction μ and
28 mechanical efficiency EFF_M as a function of confined compressive strength
29 CCS of the rock. Correction factors CF_{MW} and CF_{CS} due to mud weight and
30 cutter size of bit used may also be derived from simulator tests using different
31 mud weights and bits with differing cutter sizes.

32

1 Optionally, relationships N versus CCS and WOB versus CCS may also be
2 established in steps 85 and 90. These relationships are generally based upon
3 the expert knowledge 80 of an experienced drilling engineer, bit type, and rock
4 strength.

5
6 Using the above methodology and globally applicable rock property
7 determination techniques, ROP can be determined very rapidly for numerous
8 bit types with reasonable accuracy and without any calibration.

9
10 **II. Determination of Confined Compressive Strength based upon**
11 **Rock Mechanics Principles**

12
13 The method of the present invention relies upon using an estimated apparent
14 strength of rock to the bit or confined compressive strength (CCS). The
15 preferred method of estimating CCS utilizes a well known rock mechanics
16 formula which has been adapted to more accurately estimate CCS for rocks of
17 low and limited permeability. This preferred method of calculating CCS is
18 described in co-pending application entitled "Method for Estimating Confined
19 Compressive Strength for Rock Formations Utilizing Skempton Theory " which
20 was concurrently filed with this application. A condensed description of this
21 preferred method will be described below.

22
23 An important part of the strength of a rock to resist drilling depends upon the
24 compressive state under which the rock is subjected. This apparent rock
25 strength of rock to resist drilling by a drill bit under the confining conditions of
26 drilling shall be referred to as a rock's confined compressive strength CCS.
27 Prior to drilling, the compressive state of a rock at a particular depth is largely
28 dependent on the weight of the overburden being supported by the rock.
29 During a drilling operation the bottom portion of a vertical well bore, i.e., rock in
30 the depth of cut zone, is exposed to drilling fluids rather than to the overburden
31 which has been removed.

1 Ideally, a realistic estimate of in situ pore pressure PP in a bit's depth of cut
2 zone is determined when calculating confined compressive strength CCS for
3 the rock to be drilled. This depth of cut zone is typically on the order of zero to
4 15 mm, depending on the penetration rate, bit characteristics, and bit operating
5 parameters. The preferred method of calculating CCS includes a novel way to
6 calculate the altered pore pressure PP at the bottom of the well bore
7 (immediately below the bit in the depth of cut zone), for rocks of limited
8 permeability.

9
10 While not wishing to be held to a particular theory, the following describes the
11 general assumptions made in arriving at a method for calculating confined
12 compressive strength (CCS) for rock being drilled using a drill bit and drilling
13 fluid to create a generally vertical well bore with a flat profile. Referring now to
14 FIG. 3, a bottom hole environment for a vertical well in a porous/permeable
15 rock formation is shown. A rock formation 120 is depicted with a vertical well
16 bore 122 being drilled therein. The inner periphery of the well bore 122 is filled
17 with a drilling fluid 124 which creates a filter cake 126 lining well bore 122.
18 Arrows 128 indicate that pore fluid in rock formation 120, i.e., the surrounding
19 reservoir, can freely flow into the pore space in the rock in the depth of cut zone.
20 This is generally the case when the rock is highly permeable. Also, the drilling
21 fluid 124 applies pressure to the well bore as suggested by arrows 130.

22
23 The rock previously overlying the depth of cut zone, which exerted an
24 "overburden stress or OB pressure" prior to the drilling of the well bore, has
25 been replaced by the drilling fluid 124. Although there can be exceptions, the
26 fluid pressure exerted by the drilling fluid 124 is typically greater than the in situ
27 pore pressure PP in the depth of cut zone and less than the overburden OB
28 pressure previously exerted by the overburden. Under this common drilling
29 condition, the rock in the depth of cut zone expands slightly at the bottom of the
30 hole or well bore due to the reduction of stress (pressure from drilling fluid is
31 less than overburden pressure OB exerted by overburden). Similarly, it is
32 assumed that the pore volume in the rock also expands. Contrarily, it is

1 assumed that the rock and its pores will contract in the case where drilling fluid
2 ECD pressure is greater than the removed overburden OB pressure. The
3 expansion of the rock and its pores will result in an instantaneous pore
4 pressure PP decrease in the affected region if no fluid flows into the pores of
5 the expanded rock in the depth of cut zone.

6

7 If the rock is highly permeable, the pore pressure reduction results in fluid
8 movement from the far field (reservoir) into the expanded region, as indicated
9 by arrows 128. The rate and degree to which pore fluid flows into the
10 expanded region, thus equalizing the pore pressure of the expanded rock to
11 that of the far field (reservoir pressure), is dependent on a number of factors.
12 Primary among these factors is the rate of rock alteration which is correlative to
13 rate of penetration and the relative permeability of the rock to the pore fluid.
14 This assumes that the reservoir volume is relatively large compared to the
15 depth of cut zone, which is generally a reasonable assumption. At the same
16 time, if drilling fluid or ECD pressure is greater than in situ pore pressure PP,
17 filtrate from the drilling fluid will attempt to enter the permeable pore space in
18 the depth of cut zone. The filter cake 126 built during the initial mud invasion
19 (sometimes referred to as spurt loss) acts as a barrier to further filtrate invasion.
20 If the filter cake 126 build up is efficient, (very thin and quick, which is desirable
21 and often achieved) it is reasonable to assume that the impact of filtrate
22 invasion on altering the pore pressure PP in the depth of cut region is negligible.
23 It is also assumed that the mud filter cake 126 acts as an impermeable
24 membrane for the typical case of drilling fluid pressure being greater than pore
25 pressure PP. Therefore, for highly permeable rock drilled with drilling fluid, the
26 pore pressure in the depth of cut zone can reasonably be assumed to be
27 essentially the same as the in-situ pore pressure PP of the surrounding
28 reservoir rock.

29

30 For substantially impermeable rock, such as shale and very tight non-shale, it is
31 assumed that there is no substantial amount of pore fluid movement or filtrate
32 invasion into the depth of cut zone. Therefore, the instantaneous pore

1 pressure in the depth of cut zone is a function of the stress change on the rock
2 in the depth of cut zone, rock properties such as permeability and stiffness, and
3 in-situ pore fluid properties (primarily compressibility).

4

5 Confined compressive strength is determined based upon the unconfined
6 compressive strength of the rock and the confining or differential pressure
7 applied to the rock during drilling. Equation (2) represents one widely practiced
8 and accepted "rock mechanics" method for calculating confined compressive
9 strength of rock.

10

$$11 \quad CCS = UCS + DP + 2DP \sin FA / (1 - \sin FA) \quad (2)$$

12 where: UCS = rock unconfined compressive strength;

13 DP = differential pressure (or confining stress) across
14 the rock; and

15 FA = internal angle of friction of the rock.

16

17 In the preferred and exemplary embodiment of the present invention, the
18 unconfined compressive strength UCS and internal angle of friction FA is
19 calculated by the processing of acoustic well log data or seismic data. Those
20 skilled in the art will appreciate that other methods of calculating unconfined
21 compressive strength UCS and internal angle of friction FA are known and can
22 be used with the present invention. By way of example, and not limitation,
23 these alternative methods of determining UCS and FA include alternative
24 methods of processing of well log data, and analysis and/or testing of core or
25 drill cuttings.

26

27 Theoretical details regarding the internal angle of friction can be found in U.S.
28 Patent No. 5,416,697, to Goodman, entitled "Method for Determining Rock
29 Mechanical Properties Using Electrical Log Data", which is hereby incorporated
30 by reference in its entirety. Goodman utilizes an expression for the angle of
31 internal friction disclosed by Turk and Dearman in 1986 in "Estimation of
32 Friction Properties of Rock from Deformation Measurements", Chapter 14,

1 Proceedings of the 27th U.S. Symposium on Rock Mechanics, Tuscaloosa,
2 Ala., Jun. 23-25, 1986. The function predicts that as Poisson's ratio changes
3 with changes in water saturation and shaliness, the angle of internal friction
4 changes. The angle of internal friction is therefore also related to rock drillability
5 and therefore to drill bit performance. Adapting this methodology to the bottom
6 hole drilling conditions for permeable rock is accomplished by defining
7 differential pressure DP as equivalent circulating density ECD pressure minus
8 the in-situ pore pressure PP. This results in the mathematical expressions for
9 CCS_{HP} and DP as described above with respect to equation (2). Equation (2)
10 assumes that friction angle FA is linear across a range of CCS. Equations may
11 also be used which do not make this linearity assumption for FA.

12

13 ECD pressure is most preferably calculated by directly measuring pressure with
14 down hole tools. Alternatively, ECD pressure may be estimated by adding a
15 reasonable value to mud pressure or calculating with software. Those skilled in
16 the art will appreciate that other ways of determining the mud or ECD pressure
17 may be used with the present invention to estimate CCS for a rock.

18

19 Rather than assuming the pore pressure PP in low permeability rock is
20 essentially zero, the present invention ideally utilizes a soil mechanics
21 methodology to determine the change in pore pressure PP and applies this
22 approach to the drilling of rocks. For the case of impermeable rock, a
23 relationship described by Skempton, A.W.: "Pore Pressure Coefficients A and
24 B," *Geotechnique* (1954), Vol. 4, pp 143-147 is adapted for use with Equation
25 (1). Skempton pore pressure may generally be described as the in-situ pore
26 pressure PP of a porous but generally non-permeable material modified by the
27 pore pressure change ΔPP due to the change in average stress on a volume of
28 the material assuming that permeability is so low that no appreciable flow of
29 fluids occurs into or out of the material. In the present application, the porous
30 material under consideration is the rock in the depth of cut zone and it is
31 assumed that that permeability is so low that no appreciable flow of fluids
32 occurs into or out of the depth of cut zone.

1

2 This differential pressure DP across the rock in the depth of cut zone may be
3 mathematically expressed as:

4

$$5 \quad DP = ECD - (PP + \Delta PP) \quad (3)$$

6

7 where: DP = differential pressure across the rock;
8 ECD = Equivalent Circulating Density of the drilling fluid;
9 (PP + ΔPP) = Skempton pore pressure;
10 PP = Pore Pressure prior to drilling in the rock; and
11 ΔPP = change in pore pressure due to ECD pressure
12 replacing earth stress.

13

14 Skempton describes two pore pressure coefficients A and B, which determine
15 the change in pore pressure ΔPP caused by changes in applied total stress for
16 a porous material under conditions of zero drainage. The change in pore
17 pressure, ΔPP, is given in the general case by:

18

$$19 \quad \Delta PP = B[(\Delta \sigma_1 + \Delta \sigma_2 + \Delta \sigma_3)/3 +$$

$$20 \quad \sqrt{\frac{1}{2}[(\Delta \sigma_1 - \Delta \sigma_2)^2 + (\Delta \sigma_1 - \Delta \sigma_3)^2 + (\Delta \sigma_2 - \Delta \sigma_3)^2]} * (3A - 1)/3] \quad (4)$$

21

22 where: A = coefficient that describes change in pore pressure
23 caused by change in shear stress;
24 B = coefficient that describes change in pore pressure
25 caused by change in mean stress;
26 σ_1 = first principal stress;
27 σ_2 = second principal stress;
28 σ_3 = third principal stress; and
29 Δ = operator describing the difference in a particular
30 stress on the rock before drilling and during
31 drilling.

1 For a generally vertical well bore, the first principal stress σ_1 is the overburden
 2 pressure OB prior to drilling which is replaced by the ECD pressure applied to
 3 the rock during drilling, and σ_2 and σ_3 are horizontal principal earth stresses
 4 applied to the stress block. Also, $(\Delta\sigma_1 + \Delta\sigma_2 + \Delta\sigma_3)/3$ represents the change in
 5 average, or mean stress, and

6 $\sqrt{\frac{1}{2}[(\Delta\sigma_1 - \Delta\sigma_2)^2 + (\Delta\sigma_1 - \Delta\sigma_3)^2 + (\Delta\sigma_2 - \Delta\sigma_3)^2]}$ represents the change in
 7 shear stress on a volume of material.

8

9 For an elastic material it can be shown that $A=1/3$. This is because a change in
 10 shear stress causes no volume change for an elastic material. If there is no
 11 volume change then there is no pore pressure change (the pore fluid neither
 12 expands nor compresses). If it is assumed that the rock near the bottom of the
 13 hole is deforming elastically, then the pore pressure change equation can be
 14 simplified to:

15

$$16 \quad \Delta PP = B(\Delta\sigma_1 + \Delta\sigma_2 + \Delta\sigma_3)/3 \quad (5)$$

17

18 For the case where it is assumed that σ_2 is generally equal to σ_3 , then

19

$$20 \quad \Delta PP = B(\Delta\sigma_1 + 2\Delta\sigma_3)/3 \quad (6)$$

21

22 Equation (5) describes that pore pressure change ΔPP is equal to the constant
 23 B multiplied by the change in mean, or average, total stress on the rock. Note
 24 that mean stress is an *invariant* property. It is the same no matter what
 25 coordinate system is used. Thus the stresses do not need to be principal
 26 stresses. Equation (5) is accurate as long as the three stresses are mutually
 27 perpendicular. For convenience, σ_z will be defined as the stress acting in the
 28 direction of the well bore and σ_x and σ_y as stresses acting in directions
 29 mutually orthogonal to the direction of the well bore. Equation (5) can then be
 30 rewritten as:

31

$$\Delta PP = B(\Delta\sigma_z + \Delta\sigma_x + \Delta\sigma_y)/3 \quad (7)$$

2

3 There will be changes in σ_x and σ_y near the bottom of the hole. However,
 4 these changes are generally small when compared to $\Delta\sigma_z$ and can be
 5 neglected for a simplified approach. Equation (7) then simplifies to

6

$$\Delta PP = B(\Delta\sigma_z)/3 \quad (8)$$

8

9 For most shale, B is between 0.8 and ~1.0. Young, soft shale have B values of
 10 0.95 to 1.0, while older stiffer shale will be closer to 0.8. For a simplified
 11 approach that does not require rock properties, it is assumed that $B=1.0$. Since
 12 $\Delta\sigma_z$ is equal to $(ECD - \sigma_z)$ for a vertical well bore, equation (8) can be rewritten
 13 as

14

$$\Delta PP = (ECD - \sigma_z)/3 \quad (9)$$

16

17 Note that ΔPP is almost always negative. That is, there will be a pore pressure
 18 decrease near the bottom of the hole due to the drilling operation. This is
 19 because ECD pressure is almost always less than the in situ stress parallel to
 20 the well (σ_z)

21

22 The altered pore pressure (Skempton pore pressure) near the bottom of the
 23 hole is equal to $PP + \Delta PP$, or $PP + (ECD - \sigma_z)/3$. This can also be expressed
 24 as:

25

$$PP - (\sigma_z - ECD)/3. \quad (10)$$

27

28 For the case of a vertical well, σ_z is equal to the overburden stress or OB
 29 pressure which is removed due to the drilling operation.

30 In the case of a vertical well and most shale (not unusually hard and stiff), the
 31 change in average stress can be approximated by the term " $(OB-ECD)/3$ ".

1 Utilizing this assumption, the following expression can be used for generally
2 vertical well bores wherein low permeability rock is being drilled:

3

$$4 \quad CCS_{LP} = UCS + DP + 2DP \sin FA / (1 - \sin FA); \quad (11)$$

$$5 \quad \text{where:} \quad DP = \text{ECD pressure} - \text{Skempton Pore Pressure}; \quad (12)$$

$$6 \quad \text{Skempton Pore Pressure} = PP - (OB - ECD) / 3 \quad (13)$$

7

$$8 \quad \text{where:} \quad OB = \text{Overburden pressure or stress } \sigma_z \text{ in the z-direction};$$

$$9 \quad \text{and}$$

$$10 \quad PP = \text{in situ pore pressure.}$$

11

12 Overburden OB pressure is most preferably calculated by integrating rock
13 density from the surface (or mud line or sea bottom for a marine environment).

14 Alternatively, overburden OB pressure may be estimated by calculating or
15 assuming average value of rock density from the surface (or mud line for
16 marine environment). In this preferred and exemplary embodiment of this
17 invention, Equations (2) and (11) are used to calculate confined compressive
18 strength for high and low permeability rock, i.e. " CCS_{HP} " and " CCS_{LP} ". For
19 intermediate values of permeability, these values are used as "end points" and
20 "mixing" or interpolating between the two endpoints is used to calculate CCS
21 for rocks having an intermediate permeability between that of low and high
22 permeability rock. As permeability can be difficult to determine directly from
23 well logs, the present invention preferably utilizes effective porosity ϕ_e .

24 Effective porosity ϕ_e is defined as the porosity fraction of the non-shale fraction
25 of rock multiplied by the fraction of non-shale rock. Effective porosity ϕ_e of the
26 shale fraction is zero. It is recognized that permeability could be used directly
27 when/if available in place of effective porosity in the methodology described
28 herein.

29

30 Although there are exceptions, it is believed that effective porosity ϕ_e generally
31 correlates well with permeability and, as such, effective porosity threshold ϕ_e is

1 used as a means to quantify the permeable and impermeable endpoints. The
 2 following methodology is preferably employed to calculate "CCS_{MIX}", the
 3 confined compressive strength of the rock to the drill bit:

4

$$5 \quad CCS_{MIX} = CCS_{HP} \text{ if } \phi_e \geq \phi_{HP}, \quad (14)$$

$$6 \quad CCS_{MIX} = CCS_{LP} \text{ if } \phi_e \leq \phi_{LP}, \quad (15)$$

$$7 \quad CCS_{MIX} = CCS_{LP} \times (\phi_{HP} - \phi_e) / (\phi_{HP} - \phi_{LP}) + CCS_{HP} \times (\phi_e - \phi_{LP}) / (\phi_{HP} - \phi_{LP})$$

$$8 \quad \text{if } \phi_{LP} \leq \phi_e \leq \phi_{HP}; \quad (16)$$

9 where: ϕ_e = effective porosity;

10 ϕ_{LP} = low permeability rock effective porosity threshold;

11 and

12 ϕ_{HP} = high permeability rock effective porosity threshold.

13

14 In this exemplary embodiment, a rock is considered to have low permeability if
 15 its effective porosity ϕ_e is less than or equal to .05 and to have a high
 16 permeability if its effective porosity ϕ_e is equal to or greater than 0.20. This
 17 results in the following values of CCS_{MIX} in this preferred embodiment:

18

$$19 \quad CCS_{MIX} = CCS_{HP} \text{ if } \phi_e \geq .20; \quad (17)$$

$$20 \quad CCS_{MIX} = CCS_{LP} \text{ if } \phi_e \leq .05; \quad (18)$$

$$21 \quad CCS_{MIX} = CCS_{LP} \times (.20 - \phi_e) / .15 + CCS_{HP} \times (\phi_e - .05) / .15 \quad (19)$$

$$22 \quad \text{if } .05 < \phi_e < .20.$$

23

24 As can be seen from the equations above, the assumption is made that the
 25 rock behaves as impermeable if ϕ_e is less than or equal to 0.05 and as
 26 permeable if ϕ_e is greater than or equal to 0.20. The endpoint ϕ_e values of
 27 0.05 and 0.20 are assumed, and it is recognized that reasonable endpoints for
 28 this method are dependent upon a number of factors including the drilling rate.
 29 Those skilled in the art will appreciate that other endpoints may be used to
 30 define the endpoints for low and high permeability. Likewise, it will be
 31

1 appreciated that non-linear interpolation schemes can also be used to estimate
2 CCS_{MIX} between the endpoints. Further, other schemes of calculating CCS_{MIX}
3 for a range of permeabilities may be used which rely, in part, upon the
4 Skempton approach described above for calculating pore pressure change
5 ΔPP which is generally mathematically described using Equations (4-9).

6
7 Calculations for CCS may be modified to account for factors such as (1) the
8 deviated angle from vertical at which the well bore is being drilled, (2) stress
9 concentrations in the depth of cut zone; and (3) effects of the profile or shape of
10 the well bore due to the geometry of the drill bit being used to create the well
11 bore. These calculations are described in co-pending patent application
12 entitled, "Method for Estimating Confined Compressive Strength for Rock
13 Formation Utilizing Skempton Theory".

14
15 FIG. 4 illustrates that using Skempton theory in conjunction with equation (3)
16 produces values for differential pressure DP that corresponds well with
17 differential pressure DP arrived at using a finite element modeling. The finite
18 element model and results corresponding to FIG. 4 are described in Warren,
19 T.M., Smith, M.B.: "Bottomhole Stress Factors Affecting Drilling Rate at Depth,"
20 *J. Pet. Tech.* (Aug. 1985) 1523-1533.

21 While the above description provides the preferred mode for calculating CCS,
22 those skilled in the art will appreciate that other methods of determining CCS
23 may also be used in conjunction with this invention to calculate ROP and make
24 other estimations based on CCS of rocks. By way of example, and not
25 limitation, one alternative method of how to determine CCS is described in U.S.
26 Patent 5,767,399 to Smith and Goldman, entitled "Method of Assaying the
27 Compressive Strength of Rock".

28

29 **III. Determination of ROP based upon Specific Energy Principles**

30 A methodology has been developed for quantitative prediction of the input
31 variables to a specific energy ROP model, except bit size as bit size is known
32 or given, based on apparent rock strength to the bit. This allows rapid

1 prediction of the expected range of ROP and drilling parameters (WOB, rpm,
2 torque) for all bit types, according to rock properties and the drilling
3 environment, i.e., (mud weight and ECD).

4
5 Specific energy (Es) principles provide a means of predicting or analyzing bit
6 performance. Es is based on fundamental principles related to the amount of
7 energy required to destroy a unit volume of rock and the efficiency of bits to
8 destroy the rock. The Es parameter is a useful measure for predicting the
9 power requirements (bit torque and rpm) for a particular bit type to drill at a
10 given ROP in a given rock type, and the ROP that a particular bit might be
11 expected to achieve in a given rock type.

12

13 Teale, R.: "The Concept of Specific Energy in Rock Drilling," *Int. J. Rock Mech.*
14 *Mining Sci.* (1965) 2, 57-53, describes the use of specific energy theory in
15 assessing bit performance. Equation 20 shows Teale's specific energy
16 equation derived for rotary drilling at atmospheric conditions.

17

$$18 \quad E_s = \frac{WOB}{A_B} + \frac{120 * \pi * N * T}{A_B * ROP} \quad (20)$$

19

20 where: Es = Specific energy (psi)
21 WOB = Weight on bit (pounds)
22 A_B = Borehole area (sq-in)
23 N = rpm
24 T = Torque (ft-lb_r)
25 ROP = Rate of penetration (ft/hr)
26 WOB = Weight on bit (pounds)

27

28 Pessier, R.C., Fear, M.J.: "Quantifying Common Drilling Problems with
29 Mechanical Specific Energy and Bit-Specific Coefficient of Sliding Friction,"
30 paper SPE 24584 presented at 1992 SPE Conference, Washington, D.C.,
31 October 4-7, validated Equation (1) for drilling under hydrostatic pressure.

32

1 Because the majority of field data is in the form of surface measurements of
 2 weight on bit (WOB), rpm (N), and rate of penetration (ROP), a bit-specific
 3 coefficient of sliding friction (μ) was introduced by Teale to express torque (T)
 4 as a function of WOB. This coefficient is used to compute specific input energy
 5 (E_s) values in the absence of reliable torque measurements, as follows:

$$6 \quad \mu = 36 \frac{T}{D_b * WOB} \quad (21)$$

7 where: T = bit torque (ft-lb_f);
 8 D_b = bit size (inches);
 9 μ = bit-specific coefficient of sliding friction
 10 (dimensionless); and
 11 WOB = weight on bit (lb).

12
 13 Teale also introduced the concept of minimum specific energy and maximum
 14 mechanical efficiency. The minimum specific energy is reached when the
 15 specific energy approaches or is roughly equal to the compressive strength of
 16 the rock being drilled. The mechanical efficiency (EFF_M) for any bit type is then
 17 calculated as follows:

$$19 \quad EFF_M = \frac{E_{s \min}}{E_s} * 100 \quad (22)$$

20 where: $E_{s \min}$ = Rock Strength

21
 22 The associated bit torque for a particular bit type to drill at a given ROP in a
 23 given rock type (CCS) is computed by using equation (23), which is derived
 24 from equation (20) and equation (22), as follows:

$$26 \quad T = \left(\frac{CCS}{EFF_M} - \frac{4 * WOB}{\pi * D_b^2} \right) * \left(\frac{D_b^2 * ROP}{480 * N} \right) \quad (23)$$

27 Substituting E_s in terms of mechanical efficiency EFF_M and torque T as a
 28 function of WOB and solving equation (20) for ROP, the rate of penetration can
 29 be calculated using equation (1) as described above.

1 **Specific Energy ROP (SEROP) Model**

2
3 The present invention ideally predicts the coefficients required in Equation (1)
4 as a function of rock strength CSS. These predictions of coefficients are
5 performed for a number of predominant bit types, including steel tooth, insert
6 tooth, PDC, TSP, impregnated, and natural diamond bit types. More
7 particularly, relationships for (1) the coefficient of sliding friction μ and (2) the
8 mechanical efficiency EFF_M , and preferably for (3) WOB, and (4) bit speed N is
9 determined for a number of types of bits as a function of apparent rock strength
10 or CCS to the bit.

11
12 Equation (1) is used to calculate ROP for multiple bit types. Ideally, three ROPs
13 are calculated for each bit type: a minimum ROP, a maximum ROP, and an
14 average or nominal ROP. These computations are possible because three
15 mechanical efficiencies (minimum efficiency, maximum efficiency, and nominal
16 efficiency) are determined from the full-scale simulator tests for each bit type.

17 18 **Full-scale Simulator Tests**

19
20 Full-scale simulator tests were conducted at Hughes Christensen facilities in
21 the Woodlands, Texas using a pressurized vessel test rig to determine sliding
22 coefficient of friction μ and mechanical efficiency EFF_M for a select number of
23 types of drill bits. Detailed information about this facility and full-scale simulator
24 test procedures can be found in the 1999 ASME ETCE99-6653 technical paper
25 titled "Re-Engineered Drilling Laboratory is a Premium Tool Advancing Drilling
26 Technology by Simulating Downhole Environments".

27
28 The drilling simulator, which is capable of testing bits up to 12-1/4" in diameter,
29 reproduces downhole conditions. It is equipped with a high-pressure drilling
30 simulator and uses full-scale bits. The laboratory is capable of re-creating the
31 geostatic stresses in the well bore at equivalent drilling depths of up to 20,000 ft
32 with typical drilling fluids.

33

1 Drilling parameters, weight on bit WOB, rotary speed N, rate of penetration
2 ROP, torque T, and bit hydraulics are computer controlled and/or recorded
3 throughout the individual test. Typically torque T is recorded. One of two
4 variables WOB and ROP are controlled with the other being a measured
5 response. This data is then used to compute bit-specific coefficient of sliding
6 friction (μ), mechanical efficiency (EFF_M), and specific energy (E_s) for each test
7 and bit type.

8
9 Rock samples with confined compressive strength ranging from 5,000 to
10 75,000 psi were used to develop the relationships for μ , and EFF_M as a function
11 of confined compressive strength (CCS) for all bit types.

12
13 The following rock samples were used:

- 14 - Catoosa Shale
- 15 - Mancos Shale
- 16 - Carthage Marble
- 17 - Crab Orchard Sandstone
- 18 - Mansfield Sandstone

19
20 From this test, three points are derived to develop the relationships for μ and
21 EFF_M for an 8-1/2" roller cone bit for hard formations. These points are:

22
23 $\mu = 0.11$ at 66,000 psi
24 Minimum $EFF_M = 19\%$ at 66,000 psi
25 Maximum $EFF_M = 44\%$ at 66,000 psi
26 CCS = 66,000 psi

27
28 **Bit Types in the ROP Model**

29
30 The following bit types were tested:

31
32 Steel Tooth bits (ST);

- 1 Tungsten Carbide Insert bits (TCI_SF) for soft formations;
- 2 Tungsten Carbide Insert bits (TCI_MF) for medium formations;
- 3 Tungsten Carbide Insert bits (TCI_HF) for hard formations;
- 4 Polycrystalline Diamond Compact bits (PDC):
 - 5 - PDC bits with 3 to 4 blades;
 - 6 - PDC bits with 5 to 7 blades;
 - 7 - PDC bits with more than 7 blades;
- 8 Natural Diamond bits (ND);
- 9 Impregnated bits (IMPREG);
- 10 Thermally Stable Polycrystalline bits (TSP);
- 11 Universal Roller Cone bits (ST and TCI bits);
- 12 Universal PDC bits (all PDC bits); and
- 13 Universal ND and TSP bits.

14

15 FIG. 5 shows data from one of the tests conducted to determine bit coefficient
16 of sliding friction μ , mechanical efficiency EFF_M , and specific energy for a
17 particular combination of bit type, environment, and confined rock strength
18 CCS. The test data shown in FIG. 5 provided values for torque at several
19 WOB/ROP pairs for a given bit type and CCS, and from which E_s , μ and EFF_M
20 are calculated.

21

22 **Bit-Specific Coefficient of Sliding Friction (μ)**

23

24 An example of how a relationship between a bit-specific coefficient of sliding
25 friction μ and confined compressive strength CCS is determined from multiple
26 tests is illustrated in FIG. 6. In this case the bit is a PDC bit with more than
27 seven blades. Rock samples from Crab Orchard Sandstone, Catoosa shale,
28 and Carthage Marble were used for multiple tests with a PDC bit with more
29 than seven blades. All tests used a mud weight of 9.5 ppg. The corresponding
30 CCS values at 6,000 psi bottom hole pressure were 18,500 psi for Catoosa
31 shale, 36,226 psi for Carthage Marble, and 66,000 psi for Crab Orchard.

32

1 The correlation established from this test data and then used to compute μ as a
2 function of CCS for a PDC bit with more than seven blades, derived from FIG.
3 6, is shown in equation (24).

4

$$5 \quad \mu = 0.9402 * \text{EXP}(-8E-06 * \text{CCS}) \quad (24)$$

6

7 The same procedure and full-scale simulator tests were performed to
8 determine the relationships of μ as a function of confined compressive strength
9 CCS for all bit types.

10

11 **Mechanical Efficiency (EFF_M)**

12

13 As shown in FIG. 5, E_s changes as drilling parameters change. Consequently,
14 E_s can not be represented by a single accurate number. Minimum and
15 maximum values of E_s were computed from each full-scale simulator test, and
16 these values were used to compute minimum and maximum mechanical
17 efficiencies for each test. For example, the test data from FIG. 5 indicates a
18 mechanical efficiency in the range of approximately 19% to 44% for this test.

19

20 FIG. 7 illustrates the relationships of minimum and maximum mechanical
21 efficiencies for PDC bits with more than seven blades as derived from test data.
22 The relationships derived from FIG. 7 and shown in Equations (25) and (26) are
23 then used to compute the minimum efficiency (Min EFF_M) and maximum
24 efficiency (Max EFF_M) as a function of CCS for PDC bits with more than seven
25 blades are as follows:

26

$$27 \quad \begin{aligned} \text{Min EFF}_M &= 0.0008 * \text{CCS} + 8.834 \\ \text{Max EFF}_M &= 0.0011 * \text{CCS} + 13.804 \end{aligned} \quad (25 \text{ and } 26)$$

28 A nominal mechanical efficiency (Nom EFF_M) is the average efficiency derived
29 from the minimum and maximum efficiencies. Equation (27) indicates the Nom
30 EFF_M for PDC bits with more than seven blades.

1 $Nom\ EFF_M = 0.00095 * CCS + 10.319$ (27)

2

3 Similar procedures and testing methods were applied to determine the
4 mechanical efficiencies, minimum, maximum and nominal, for all bit types.
5 These correlations are not shown in this application.

6

7 **Weight on bit (WOB) and bit rpm**

8

9 Drilling parameters WOB and N are variables that are selected based on a
10 number of factors, including but not limited to field experience, bit type, and/or
11 bottom hole (BHA) configuration. However, the present invention also has the
12 capability of predicting the appropriate WOB and N based on CCS.

13

14 FIG. 9 shows the relationship between WOB factor (pounds force per inch of bit
15 diameter) and CCS, and the relationship between WOB for an 8.5" steel tooth
16 bit and CCS. FIG. 9 shows the relationship between N (RPM for roller cone
17 bits) and CCS.

18

19 **Adjustments to μ and EFF_M due to Drilling Environment**

20

21 The efficiency of drill bits is affected by mud weight. The magnitude of
22 efficiency change arising from changes in mud weight has been determined by
23 performing additional tests that use different mud weight systems. Because full-
24 scale simulator tests for all bit types were performed using a 9.5 ppg mud
25 weight, the potential effect of mud weight on μ and EFF_M was evaluated using a
26 heavier mud weight. Consequently, full-scale tests were performed for all bit
27 types using a 16.5 ppg mud weight.

28

29 It has been determined that the value of μ for PDC bits is reduced by
30 approximately 49% when increasing mud weight from 9.5 ppg to 16.5 ppg. As a
31 result, the value of μ is preferably corrected if the mud weight is different from

1 9.5 ppg. From FIG. 10, the following correction factor for coefficient of sliding
2 friction μ for PDC bits with more than seven blades was established.

3

$$4 \quad CF_{\mu} = -0.8876 * \ln(\text{mud weight}) + 2.998 \quad (28)$$

5

6 Equation (29) is a revised formula for computing the value of μ for any mud
7 weight.

8

$$9 \quad \mu = [(0.9402 * \text{EXP}(-8E - 06 * \text{CCS})) * \quad (29) \\ [-0.8876 * \ln(\text{MudWeight}) + 2.998]$$

10

11 It was determined that mechanical efficiency for PDC bits was reduced by
12 approximately 56% when increasing the mud weight from 9.5 ppg to 16.5 ppg.
13 FIG. 11 establishes the following correction factor to EFF_M for PDC bits with
14 more than seven blades:

15

$$16 \quad CF_{EFFM} = -1.0144 * \ln(\text{Mud Weight}) + 3.2836 \quad (30)$$

17

18 Equations (31) and (32) show the revised correlations for Min and Max
19 mechanical efficiencies for PDC bits with more than seven blades.

$$20 \quad \text{Min } EFF_M = [-0.0008 * \text{CCS} + 8.834] * \quad (31) \\ 21 \quad [1.0144 * \ln(\text{Mud Weight}) + 3.2836]$$

$$22 \quad \text{Max } EFF_M = [-0.0011 * \text{CCS} + 13.804] * \quad (32) \\ 23 \quad [1.0144 * \ln(\text{Mud Weight}) + 3.2836]$$

24 The same testing procedure was conducted to establish the correction factors
25 for μ and EFF_M for all bit types. Although the above equations are linear, as
26 are the curves shown in FIGS. 10 and 11, it is recognized that non-linear
27 relationships may, in fact, be valid and more realistic. Accordingly, those
28 skilled in the art may preferably employ such non-linear equations/relationships
29 when appropriate.

1 Correction Factor for PDC Bits due to Cutter Size

2

3 To account for the effect of cutter size for PDC bits in the ROP model, full-scale
 4 simulator tests were performed using various cutter sizes with PDC bits. FIG.
 5 12 illustrates the effect of cutter size with PDC bits. Because full-scale
 6 simulator tests for PDC bits were performed using drill bits with 19 mm cutters,
 7 additional tests were performed with cutter size greater than or less than 19
 8 mm. The test results indicated that the bit coefficient of sliding friction μ is
 9 decreased or increased by 1.77% when the cutter size is decreased or
 10 increased for each millimeter above or below 19 mm, as shown in FIG. 12.

11

12 Therefore, the correction factor to adjust μ due to cutter size is as follows:

13

$$14 \quad 0.0177 * \text{Cutter Size} + 0.6637 \quad (33)$$

15

16 where: cutter size is in millimeters.

17

18 Although the above equation indicates a linear relationship, it is recognized that
 19 non-linear relationships may, in fact, be valid and more realistic, and may
 20 preferably be employed when appropriate. This, in fact, is indicated by FIG. 11.

21

22 Combining all the correction factors, the final correlation for μ for PDC bits with
 23 more than seven blades is shown in equation (34).

$$24 \quad \mu = [(0.9402 * \text{EXP}(-8E - 06 * \text{CCS})) * \\ [-0.8876 * \text{Ln}(\text{MudWeight}) + 2.998] * \\ [0.0177 * \text{Cutter Size} + 0.6637] \quad (34)$$

25 In a similar manner, final correlations for μ for all bit types may be made for
 26 other bit types.

27

1 **Limitations of ROP Model**

2

3 The above described ROP model based upon specific energy does not take
4 into account bit design features, such as cone offset angle, cone diameter, and
5 journal angle of roller cone bits, and does not take into account design features,
6 such as back rack angle and bit profile of PDC bits. The selection of the proper
7 bit design features for each application could impact ROP. Although the impact
8 on ROP of all design features is quantitatively measured in the lab, field tests
9 using the subject ROP model indicate that the impact on ROP could be
10 between 10% and 20%. The variation of ROP as a result of bit design features
11 is assumed to be captured by the ROP model because it computes a maximum
12 and a minimum ROP as a function of maximum and minimum efficiency. In
13 fact, in most of the field examples, the nominal ROP closely correlates with
14 actual ROP, but there are a few cases in which either the minimum or the
15 maximum ROP correlate with actual ROP.

16

17 Mud systems, such as water based mud (WBM) or oil based mud/synthetic
18 based mud (OBM/SBM), are not differentiated in the specific energy ROP
19 model. However, field tests show that a significant factor affecting bit
20 performance and ROP is bit balling with WBM. If bit balling is eliminated with
21 optimum hydraulics and control of mud properties, it is assumed the predicted
22 ROP will be approximately the same for both mud systems.

23

24 The specific energy ROP model does not consider or optimize hydraulics. Full
25 scale simulator tests used to develop the ROP model were performed with
26 optimum hydraulics. Again, because the specific energy ROP model predicts
27 minimum and maximum ROP, the actual ROP typically falls within the minimum
28 and maximum ROP parameters for any bit type, provided that the actual
29 hydraulics are adequate.

30

31 The ROP model of the present invention is currently adapted only for sharp
32 bits. It does not take into account bit wear. However, ROP model may be

1 further adjusted for bit wear as bit wear and/or bit life models may be
2 developed. Examples of how bit wear and bit life may be incorporated into
3 drilling predictions are described in U.S. Patent Number 6,408,953 to Goldman,
4 entitled "Method and System for Predicting Performance of a Drilling System
5 for a Given Formation". The disclosure of this patent is hereby incorporated by
6 reference in its entirety.

7

8 Predicted ROP for PDC bits is for groups of bits based on blade count. Three
9 groups were established: PDC bits with three to four blades, PDC bits with five
10 to seven blades, and PDC bits with more than seven blades. Field tests
11 indicate that minimum ROP generally correlates with PDC bits with the highest
12 number of blades within the group and maximum ROP correlates with the
13 lowest blade count in the group.

14 Predicted ROP for roller cone bits was made for four groups of bits: steel tooth
15 bits, roller insert bits for soft formations, roller insert bits for medium formations,
16 roller insert bits for hard formations.

17

18 The specific energy ROP model doesn't account for when the CCS might
19 exceed the maximum CCS suitable for a particular bit type. As a result, with
20 the exception of very high strength rock, the specific energy ROP model
21 generally predicts that the highest ROP for a PDC bit with three to four blades,
22 the next highest ROP for a PDC bit with five to seven blades, and so forth,
23 through the range of different bit types according to aggressiveness.

24

25 **Bit Selection and Optimization**

26

27 The most common approach for evaluating drilling performance and bit
28 selection in the oil field is based on past observed performance from offset
29 wells. This methodology tends to apply the same drilling performance and rock
30 strength to the current application without evaluating changes in rock strength,
31 lithology, drilling environment, and potential ROP if other bit types are used.
32 The CCS and specific energy ROP models use rock properties and drilling
33 environments to accurately predict the potential ROP for all bit types.

1 Therefore, the present approach is global; it is not restricted to a particular area
2 or region nor does it necessarily require calibration to local conditions.

3
4 In a real-time bit optimization scenario, predicted ROP and Es energy values
5 can be used to assess bit performance. This can be accomplished if the rock
6 properties are known, either by correlation or directly measured and calculated
7 from LWD (logging while drilling) data or from drilling parameters as indicated
8 in section IV below. Bit performance and condition can be evaluated by
9 comparing actual Es to predicted Es, as well as by comparing actual ROP to
10 predicted ROP. Bit performance analysis using real time predicted Es and
11 actual Es values can be also used to detect and correct drilling problems, such
12 as bit vibration and bit balling. Predicted and actual Es values can also be used
13 in dull bit and/or bit failure analysis.

14

15 **IV. Back Calculation of UCS**

16

17 The specific energy ROP and CCS models described above can be used to
18 back calculate CCS and rock properties in the absence of log or other data.
19 The rock properties can then be used for real-time bit optimization, wellbore
20 stability and sanding or post-drill bit optimization, wellbore stability and sanding
21 or post-drill bit optimization, wellbore stability and sanding analysis.

22

23 Assuming drilling parameters are obtained during drilling, values of CCS can be
24 determined as follows: downhole torque and WOB are available from
25 downhole tools, bit-specific coefficient of sliding friction can be calculated using
26 equation (21):

$$27 \quad \mu = 36 \frac{T}{D_B * WOB}$$

28 Once the bit-specific coefficient of sliding friction has been determined using
29 equation (21), the confined compressive strength of the rock being drilled
30 (CCS) is determined by using the relationships between bit-specific coefficient

1 of sliding friction μ and confined compressive strength CCS determined for all
2 bit types (e.g. relationship in FIG 6).

3

4 Once CCS is determined, the mechanical efficiency EFF_M for any bit type is
5 derived from the relationships between minimum and maximum mechanical
6 efficiency (e.g. relationship in FIG. 7). Knowing CCS, the ROP for any bit type
7 can be calculated using equation (1) for a given set of drilling parameters
8 (WOB and N).

9

10 In the absence of downhole torque, μ can be calculated by trial and error
11 methods until predicted ROP match with actual ROP. EFF_M can be determined
12 using average values of EFF_M or determined by trial and error methods until
13 predicted ROP matches with actual ROP. Then CCS can be calculated using
14 equation (1). Further UCS can be back calculated from the CCS using
15 equation (2). Once UCS is determined, this value of UCS can be used in well
16 bore stability and sanding analysis.

17

18 EXAMPLES

19

20 The field test examples presented below illustrate how the CCS and specific
21 ROP models may be used to improved drilling performance by reducing both
22 drilling time and drilling costs. This performance is achieved by selecting the
23 optimum drill bits and drilling parameters for each application.

24

25 Well 1

26 FIG. 13 shows the drilling performance for a specific interval composed mainly
27 of dolomite in which the ROP has been very low (approximately 1 meter/hour)
28 with roller cone bits (TCI), heavy set PDC bits, and impregnated bits
29 (IMPREG). Analysis indicates that CCS ranged from about 20,000 psi to
30 35,000 psi.

31

32 Track 5 provides an example of the correlation between the predicted ROP to
33 the actual ROP for all bit types used to drill the interval. Predicted ROP is

1 calculated using actual drilling parameters (WOB, RPM) from actual bit runs
2 shown in Track 4. Track 3 shows the actual bits used and their dull grades.
3 Track 6 illustrates the potential ROP for Insert bits (TCI medium formations),
4 PDC bits with five to seven blades and 19 mm cutters (PDC 5-7B), PDC bits
5 with more than seven blades (PDC>7B), Natural Diamond (ND) bits, Thermally
6 Stable Polycrystalline (TSP) bits, and Impregnated (IMPREG) bits. The
7 predicted ROP for ND, TSP, and IMPREG bits is calculated using global
8 defaults in the specific energy ROP model.

9
10 The analysis suggested that neither roller cone bits nor Impreg bits are suitable
11 for this application because of low ROP. The analysis indicated that PDC bits
12 with five to seven blades and 19 mm cutters could deliver a ROP between 6
13 and 8 meters per hour (WOB between 10 and 20 Klbs and N between 120 and
14 160 rpm). Although, a PDC bits with three to four blades will deliver a higher
15 ROP (not shown here), this bit was not considered because the high rock
16 strength exceeds the bits rock strength capability. As a result, the
17 recommended approach is to use a six bladed PDC bit with 19 mm abrasive
18 resistance cutters and thinner diamond tables (less than 0.120 inches
19 thickness). Wells can now be drilled at an average ROP of 6 to 8 meters per
20 hour.

21

22 **Well 2**

23 FIG. 14 provides another example of the use of the CCS and specific energy
24 ROP model to select the optimum bit for an exploratory well. Log data and
25 drilling data from offset wells are used to create a composite for the proposed
26 well, and then rock mechanics and specific energy ROP analysis are
27 performed.

28

29 The evaluation shows that the interval is comprised of low strength rock with
30 CCS ranging between 3,000 psi and 5,000 psi, and that the interval can be
31 drilled with an aggressive PDC bit. The recommended approach is to use a five
32 bladed PDC bit with 19 mm abrasive resistance cutters. The well is drilled at

1 ROP rate of 160 to 180 ft/hr. Although the lithology in the well drilled is not
2 exactly the same as the offset wells, the predicted ROP (solid line, track 4)
3 closely correlates with actual ROP achieved in well drilling.

4

5 **Well 3**

6 FIG. 15 shows the drilling performance for an 8-1/2 in. hole drilled using PDC
7 bits with seven and nine blades. The well was drilled at a ROP of 20 to 40 ft/hr.
8 FIG. 15 also illustrates the bit optimization performed for a sidetrack out of the
9 same well bore. Rock mechanics analysis indicates that the CCS for the
10 interval (CCS, track 2) is between 8,000 psi to 10,000 psi and that the well
11 could be drilled with a more aggressive PDC bits than the bits used to drill the
12 original well bore. The analysis suggested that the sidetrack be drilled with a six
13 bladed PDC bit with 19 mm cutters to achieve better penetration rates. See the
14 actual ROP achieved in original well bore in track 4 and predicted ROPs for the
15 sidetrack in track 5.

16 The sidetrack was drilled with one PDC bit at ROP of 60 to 80 ft/hr. The
17 sidetrack was drilled in four days rather than eight days required to drill the
18 original wellbore.

19

20 **Well 4**

21 FIG. 16 shows how the CCS and SEROP models can be used to assess bit
22 performance real-time, and thereby optimize drilling performance. Predicted Es
23 and ROP values can be used to determine whether or not the bit is performing
24 efficiently or whether or not bit efficiency is affected by bit vibration, bit balling,
25 and/or dull bits.

26

27 FIG. 16 illustrates that the first bit drilled the top section of interval efficiently as
28 the predicted ROP closely correlates with actual ROP (track 5). In addition,
29 actual Es also correlates with predicted Es except for shale intervals where Es
30 is several times higher than predicted Es (track 6), probably due to bit balling.

31 The second bit drilled the lower part of the section inefficiently. Neither the
32 predicted ROP nor Es matched with the actual ROP and Es. The actual Es was

1 higher than the predicted Es by more than five times, indicating that bit
2 efficiency is extremely low as a result of bit vibration and/or bit balling. The bit
3 record showed that bit was balled up.

4

5 While in the foregoing specification this invention has been described in relation
6 to certain preferred embodiments thereof, and many details have been set forth
7 for purposes of illustration, it will be apparent to those skilled in the art that the
8 invention is susceptible to alteration and that certain other details described
9 herein can vary considerably without departing from the basic principles of the
10 invention.

1 WHAT IS CLAIMED IS:

2

3 1. A method for determining the rate of penetration (ROP) of a drill bit
4 drilling a well bore through intervals of rock of a subterranean formation, the
5 method comprising the steps of:

6 a) determining for at least one type of drill bit a relationship between
7 a bit-specific coefficient of sliding friction μ and confined compressive strength
8 CCS over a range of confined compressive strengths CCS;

9 b) determining for the at least one type of drill bit a relationship
10 between mechanical efficiency EFF_M and confined compressive strength CCS
11 over a range of confined compressive strengths CCS;

12 c) determining the confined compressive strength for intervals of
13 rock through which the at least one type of drill bit is to be drilled to form a well
14 bore; and

15 d) calculating the rate of penetration ROP for the at least one type of
16 drill bit drilling along the intervals of rock to create a well bore, the calculations
17 utilizing the confined compressive strength of the intervals of rock being drilled
18 and the relationships between the bit-specific coefficient of sliding friction μ and
19 the mechanical efficiency EFF_M and the confined compressive strengths CCS.
20

21 2. The method of claim 1 wherein:

22 the relationship between the bit-specific coefficient of sliding friction μ
23 and the confined compressive strength CCS over a range of confined
24 compressive strengths CCS for the at least one type of drill bit is dependent
25 upon the weight of the drilling fluid being used to drill an interval of rock.
26

27 3. The method of claim 1 wherein:

28 the relationship between the bit-specific coefficient of sliding friction μ
29 and the confined compressive strength CCS over a range of confined
30 compressive strengths CCS is dependent upon the size of the cutters for
31 polycrystalline diamond compound (PDC) bits.

32 4. The method of claim 1 wherein:

1 the relationship between the mechanical efficiency EFF_M and the
2 confined compressive strength CCS over a range of confined compressive
3 strengths CCS for at least one drill bit is dependent upon the weight of the
4 drilling fluid being used to drill the well bore.

5

6 5. The method of claim 1 further comprising:

7 determining a relationship, for the at least one type of drill bit, between
8 the revolutions per minute (N) at which the at least one type of drill bit is to be
9 operated and confined compressive strength CCS over a range of confined
10 compressive strengths CCS; and

11

12 calculating the rate of penetration ROP for the at least one type of drill
13 bit drilling through the intervals of rock to create a well bore utilizing the
14 confined compressive strength of the intervals of rock being drilled and the
15 relationships between the bit-specific coefficient of sliding friction u , the
16 mechanical efficiency Eff_M and the revolutions per minute (N) at which the drill
17 bit is to be operated and the confined compressive strengths.

18

19 6. The method of claim 1 further comprising:

20 determining a relationship for the at least one drill bit between the
21 weight on bit (WOB) at which the at least one drill bit is to be operated and
22 confined compressive strength CCS over a range of confined compressive
23 strengths CCS; and

24 calculating the rate of penetration for the at least one type of drill bit
25 drilling along the intervals of rock utilizing the confined compressive strength of
26 the intervals of rock being drilled and the relationships between the bit-specific
27 coefficient of sliding friction u , the mechanical efficiency Eff_M , and WOB at which
28 the bit should be operated and confined compressive strength.

29

- 1 7. The method of claim 1 wherein:
 2 the rate of penetration is calculated in accordance with the following
 3 mathematical expression:

$$4 \text{ } ROP = \frac{13.33 \mu N}{D_B \left(\frac{CCS}{EFF_M * WOB} - \frac{1}{A_B} \right)}$$

- 5
 6
 7 where: ROP = Rate of penetration (ft/hr);
 8 μ = bit-specific coefficient of sliding friction;
 9 N = revolutions per minute of the at least one drill bit;
 10 CCS = Confined compressive strength (psi) of the rock
 11 in the interval being drilled;
 12 WOB = weight on bit (lbs);
 13 EFF_M = Mechanical efficiency (%);
 14 D_B = Bit diameter (in); and
 15 A_B = Borehole area (sq-in) of the well bore being drilled.
 16

- 17 8. The method of claim 1 wherein:
 18 the confined compressive strength (CCS) of an interval of rock is
 19 determined at least in part based upon the unconfined compressive strength
 20 (UCS) of the interval of rock, the equivalent circulating density (ECD) of a
 21 drilling fluid being used to drill the interval of rock, the overburden stress (OB)
 22 removed from the interval of rock being drilled, the in situ pore pressure (PP) of
 23 pore fluids proximate the interval of rock being drilled, and the permeability of
 24 the interval of rock being drilled.
 25

- 26 9. The method of claim 8 wherein:
 27 CCS is calculated in accordance with the following mathematical
 28 expression for intervals of rock having low permeability:
 29

$$30 \text{ } CCS = UCS + f(DP)$$

- 31 where UCS = Unconfined Compressive Strength for the rock;
 32 and;

1 $f(DP)$ = function of the differential pressure DP applied
 2 across the rock during drilling.

3

4 10. The method of claim 8 wherein:

5 CCS is calculated in accordance with the following mathematical
 6 expression for intervals of rock having low permeability:

7

$$8 \quad CCS_{LP} = UCS + DP_{LP} + 2DP_{LP}\sin FA / (1 - \sin FA);$$

9

10 where: $DP_{LP} = ECD \text{ pressure} - (PP - (OB - ECD)/3);$

11 ECD = Equivalent Circulating pressure;

12 PP = in situ Pore Pressure; and

13 OB = Overburden pressure.

14

15 11. The method of claim 10 wherein:

16 CCS is calculated in accordance with the following mathematical
 17 expression for intervals of rock having high permeability:

18

$$19 \quad CCS = UCS + DP + 2DP\sin FA / (1 - \sin FA)$$

20 where: UCS = Unconfined Compressive Strength of the rock;

21 DP = ECD – PP;

22 DP = differential pressure between bottom

23 hole pressure exerted by ECD and in-situ pore pressure;

24 and

25 FA = the internal angle of friction of the rock.

26

27 12. The method of claim 1 wherein:

28

29 the step of determining relationships between the coefficient of sliding
 30 friction μ and the mechanical efficiency Eff_M of at least one drill bit as a varying
 31 function of a range of confined compressive strengths is bit wear dependent.

32

1 13. A method for back calculating confined compressive strength CCS of
 2 rock in an interval of a subterranean formation in which a well bore has been
 3 drilled using a type of drill bit and drilling fluids, the method comprising the
 4 steps:

5
 6 a) measuring (i) the rate of penetration (ROP) ; (ii) weight on bit (WOB); (iii)
 7 bit torque T; and (iv) the revolutions per minute (N) used during the drilling
 8 through an interval of rock in a subterranean formation by the type of drill bit;

9
 10 b) estimating the coefficient of sliding friction μ during the drilling through
 11 the interval of rock; and

12
 13 c) selecting a value of CCS from a predetermined relationship between μ
 14 and CCS for the type of drill bit.

15
 16 14. The method of claim 13 wherein:

17 estimating the coefficient of sliding friction μ is calculated in accordance
 18 with the following mathematical expression:

19
$$\mu = 36 \frac{T}{D_b * WOB}$$

20 where: T = bit torque (ft-lb_f);

21 D_b = bit size (inches);

22 μ = bit-specific coefficient of sliding friction
 23 (dimensionless); and

24 WOB = weight on bit (lbs).

25
 26 15. The method of claim 13 further comprising:

27
 28 determining the mechanical efficiency EFF_M of the drill bit utilizing a
 29 predetermined relationship between EFF_M and CCS.

30
 31
 32 16. The method of claim 13 wherein:

mechanical efficiency EFF_M is calculated in accordance with the mathematical equation:

$$ROP = \frac{13.33 \mu N}{D_B \left(\frac{CCS}{EFF_M * WOB} - \frac{1}{A_B} \right)}$$

where: ROP = Rate of penetration (ft/hr);

μ = bit-specific coefficient of sliding friction;

N = revolutions per minute of the at least one drill bit;

CCS = Confined compressive strength (psi) of the rock in the interval being drilled;

WOB = weight on bit (lbs);

EFF_M = Mechanical efficiency (%);

D_B = Bit diameter (in); and

A_B = Borehole area (sq-in) of the well bore being drilled.

17. The method of claim 13 further comprising:

back calculating the unconfined compressive strength UCS of the rock in the interval in accordance with the following mathematical expression:

$$CCS = UCS + DP + 2DP \sin FA / (1 - \sin FA)$$

where: UCS = rock unconfined compressive strength;

DP = differential pressure (or confining stress) across the rock; and

FA = internal angle of friction of the rock.

18. A real-time method for analyzing the performance of a drill bit during drilling of a wellbore, the method comprising:

estimating one of ROP or specific energy E_s during drilling of a well bore;

measuring the actual ROP during drilling of the well bore or calculating

measured specific energy using measured drilling parameters; and

determining the performance of the bit by comparing the measured ROP or measured specific energy E_s against predicted ROP or predicted specific energy.