Operational Performance Requirements For Motor Power Sections Used in Geothermal Drilling Based Upon Minimum Specific Energy

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Abstract

Operational performance requirements are needed to support development of specifications for downhole motor power sections to be used for drilling hard rock during geothermal wellbore construction. Theoretical torque specifications are derived based upon a widely-accepted rock-reduction model in the literature using representative properties for typical rock formations. The derived values correspond to optimum motor performance for rock reduction at minimum specific energy and form a set of minimum requirements on output torque and power for downhole motors. Actual values should be increased to account for factors such as increased hydrostatic pressure at depth, bit wear, heterogeneous rock, and non-ideal drilling conditions.

Technical Approach

The approach uses a method to predict motor performance requirements for drilling at minimum specific energy. While field drilling rarely proceeds at minimum specific energy, this condition corresponds to maximum drilling efficiency and preferred operational loads. Requisite torque and power values are derived corresponding to minimum specific energy for various drilling conditions. These values are derived for a series of bit diameters drilling a variety of rock types across a range of operating conditions. Derived values may be subsequently used to compare performance envelopes for existing downhole motors. While downhole motors presently provided by the energy services industry are inadequate for drilling at high temperature or in high-strength rock characteristic of geothermal formations, the data derived herein will allow the suitability of existing motors to be assessed relative to minimum required performance metrics anticipated for geothermal drilling.

Following the method from Reference 1 and summarized in Appendix A, the governing expression for the operational torque, T, for a drag bit to drill a formation of Unconfined Compressive Strength (UCS), at minimum specific energy is:

$$T = \frac{d^2}{8}\varepsilon*\delta \quad \text{[ft-lb]}$$

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where d is the bit diameter (inches), ε is the UCS of the rock (psi), and δ is the depth of cut per revolution (ft/rev).

The depth of cut is

$$\delta = ROP/(60N) \quad \text{[ft/rev]} \quad = \quad ROP/(5N) \quad \text{[in/rev]}$$

where ROP is the rate of penetration (ft/hr), and N is the rotary speed (RPM).

This operational torque will increase in proportion to the hydrostatic pressure with increasing depth. Hence the method predicts the required torque at atmospheric operating conditions and must be increased in proportion to bottom-hole pressure.

The delivered power, P, is

$$P = T * N * 2\pi/(60*550) \quad \text{[hp]}$$

Minimum Specific Energy Data

Bit diameters of 4, 6, 8, 10 & 12 inches are evaluated. Strength (UCS) values for Berea Sandstone, Arizona Sandstone, Sierra White Granite, and Mississippi Limestone are used. Rotary speeds are used comparable to what is generally practiced on PDM motors. Using these values, tabular data are generated to determine values of d^2*eta/8 in Table 1; rate of penetration, ROP, in Table 2 corresponding to a specific depth of cut, doc, and rotary speed, N; operational torque, T, in Table 3; and delivered power, P, in Table 4. These values are graphically portrayed in Figures 1 through 4.

The tables and figures may be used as a "nomograph" to derive the operational torque and power, subject to known operating conditions, as follows:

- Use Table 1 or Figure 1 to derive the d^2*eta/8 term corresponding to the bit diameter and rock type;
- Use Table 2 or Figure 2 to select the depth of cut, doc, corresponding to the target rate of penetration, ROP at the desired rotary speed, N. (A maximum depth of cut of 0.1 inch/rev is used as an upper limit as this is a large advance rate for a drag bit).
- Use Table 3 or Figure 3 to derive the torque, T, corresponding to the depth of cut, doc, and d^2*eta/8 value;
- Use Table 4 or Figure 4 to derive the power, P, corresponding to the torque, T, and rotary speed, N.

For a given bit diameter, maximum torque requirements result corresponding to conditions of maximum UCS, and maximum depth of cut per revolution. Maximum power conditions correspond to the maximum rotary speed corresponding to the depth of cut used to specify the depth of cut per revolution. Hence to drill the hardest rock identified in Table 1 (40000 psi), the following values result for operational performance requirements in Table 5. These are plotted in Figure 5.

Table 1. Rock-Bit interaction Parameter, d^2*eta/8 (lb.) for various bit diameters and rock types.

Rock Description	UCS (psi)	Bit Diameter (in)	d^2*eta/8 (#)
1. Berea Sandstone	11,576	4	2.32E+04
	11,576	6	5.21E+04
	11,576	8	9.26E+04
	11,576	10	1.45E+05
	11,576	12	2.08E+05
2. Arizona Sandstone	20,580	4	4.12E+04
	20,580	6	9.26E+04
	20,580	8	1.65E+05
	20,580	10	2.57E+05
	20,580	12	3.70E+05
3. Sierra White Granite	28,200	4	5.64E+04
	28,200	6	1.27E+05
	28,200	8	2.26E+05
	28,200	10	3.53E+05
	28,200	12	5.08E+05
4. Mississippi Limestone	40,000	4	8.00E+04
	40,000	6	1.80E+05
	40,000	8	3.20E+05
	40,000	10	5.00E+05
	40,000	12	7.20E+05

Rock UCS References: 1. Reference 2, 2. Reference 3, 3. Reference 4, 4. Reference 5.

Table 2. Operating Conditions (ROP as a function of depth of cut and rotary speed).

ROP (ft/hr)	Speed (RPM)					
doc (in/rev)	50	100	200	300	400	500
0.005	1.3	2.5	5.0	7.5	10.0	12.5
0.010	2.5	5.0	10.0	15.0	20.0	25.0
0.020	5.0	10.0	20.0	30.0	40.0	50.0
0.040	10.0	20.0	40.0	60.0	80.0	100.0
0.060	15.0	30.0	60.0	90.0	120.0	150.0
0.080	20.0	40.0	80.0	120.0	160.0	200.0
0.100	25.0	50.0	100.0	150.0	200.0	250.0

Table 3. Torque as a function of depth of cut and d^2*eta/8.

Torque (ft-#)	d^2*eta/8 (#)							
doc (in/rev)	10,000	25,000	50,000	100,000	200,000	400,000	600,000	800,000
0.005	4	10	21	42	83	167	250	333
0.010	8	21	42	83	167	333	500	667
0.020	17	42	83	167	333	667	1000	1333
0.040	33	83	167	333	667	1333	2000	2667
0.060	50	125	250	500	1000	2000	3000	4000
0.080	67	167	333	667	1333	2667	4000	5333
0.100	83	208	417	833	1667	3333	5000	6667

Table 4. Power as a function of torque and rotary speed.

Power (hp)	Speed (RPM)					
Torque (ft-#)	50	100	200	300	400	500
0	0.0	0.0	0.0	0.0	0.0	0.0
500	4.8	9.5	19.0	28.6	38.1	47.6
1,000	9.5	19.0	38.1	57.1	76.2	95.2
2,000	19.0	38.1	76.2	114.2	152.3	190.4
2,500	23.8	47.6	95.2	142.8	190.4	238.0
5,000	47.6	95.2	190.4	285.6	380.8	476.0
7,500	71.4	142.8	285.6	428.4	571.2	714.0

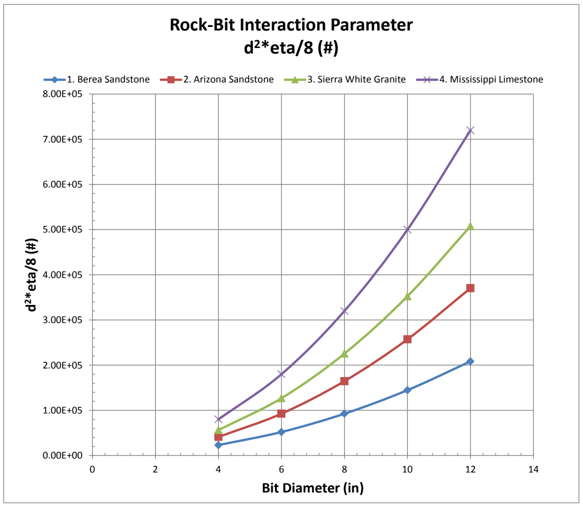


Figure 1. Rock-Bit interaction parameter vs. bit diameter for several representative rock types.

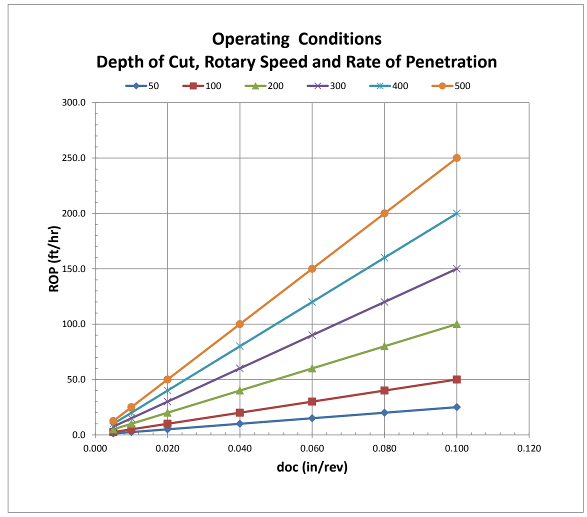


Figure 2. Rate of penetration vs. depth of cut per revolution for several rotary speeds.

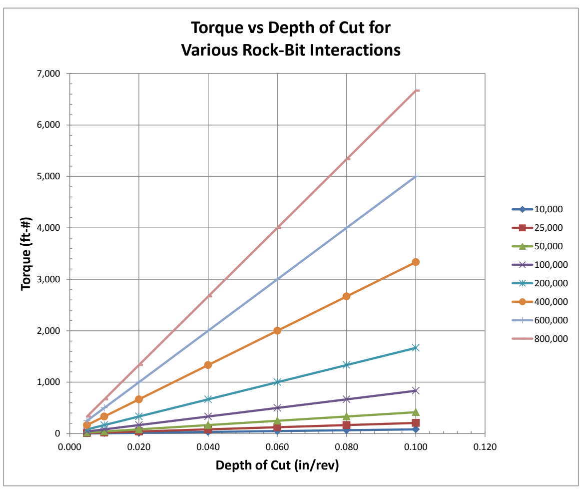


Figure 3. Operational torque vs. depth of cut for various rock-bit interaction parameters.

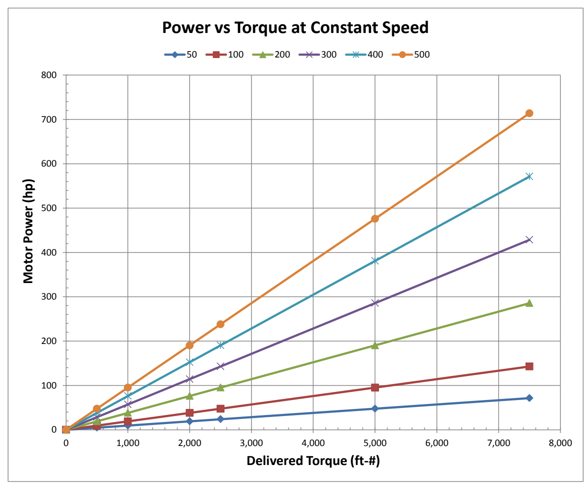


Figure 4. Operational power vs. delivered torque for several rotary speeds.

Table 5. Maximum operational performance requirements corresponding to reducing rock of 40,000 psi UCS.

Bit Diameter (in)	d^2*eta/8 (#)	doc (in/rev)	Torque (ft-#)	Speed (RPM)	Power (hp)
Range	Max	Max	Max	Max	Max
4" D	8.80E+04	0.10	733	500	70
6" D	1.98E+05	0.10	1650	500	157
8" D	3.52E+05	0.10	2933	500	279
10" D	5.50E+05	0.10	4583	500	436
12" D	7.92E+05	0.10	6600	500	628

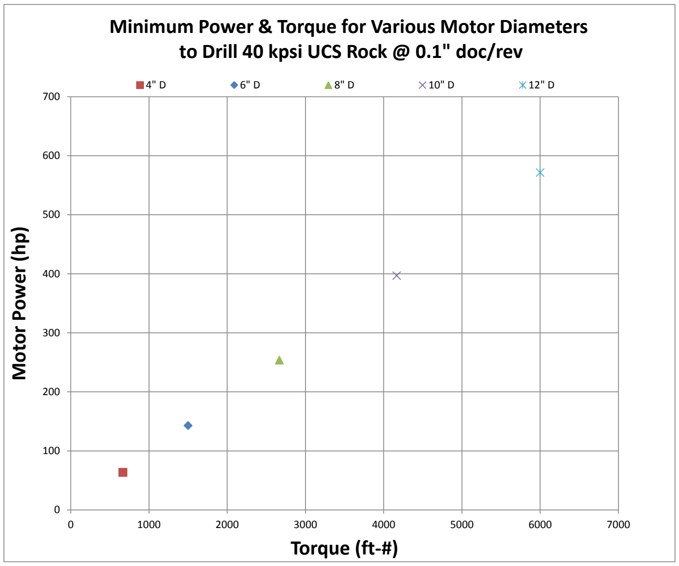


Figure 5. Minimum Power & Torque for various motor diameters to drill 40 kpsi UCS rock @ 0.1" doc/rev.

Conclusions

Operational performance requirements have been derived based upon drilling various rock types at minimum specific energy. The torque and power conditions derived herein represent minimum operational performance requirements necessary to drill the representative rock types listed in Table 1. These torque values must be increased with drilling depth (i.e., hydrostatic head) due to increased rock hardness and increased chip hold-down forces, bit wear, hard streaks in rock formations, inefficient drilling conditions requiring higher net power, and other conditions.

References

1. Detournay, E., Defourny, P., 1992, “A Phenomenological Model for the Drilling Action of Drag Bits,” Int. J. Rock Mech. Min. Sci. & Geomech. Abstr., Vol. 29, No.1, pp. 13-23.
2. Physical Properties of Berea Sandstone, Cleveland Quarries Technical Data Report, email transmittal on Aug 25, 2014.
3. Development of a Mine Rescue Drilling System, Phase I Report, Raymond, D. W., et al, SAND2014-2424.
4. Pratt, H., Black, A., 1980, “Representative Geothermal Rocks, Rock Specifications and Material Properties,” Drilling Research Laboratory, TR80-08.
5. Development of a System to Provide Diagnostics-While-Drilling, Finger, J.A., et al, SAND2003-2069.

Appendix A.

HT MOTOR PERFORMANCE REQUIREMENTS

Determine Operational Envelope based upon operating a dragbit (high torque) in various formations & operating conditions,

E_s = Specific Energy = $\dfrac{\text{Energy Expended to Drill}}{\text{Unit Rock Volume Removed}} = \dfrac{E}{\forall}$

Assume energy input dominated by rotary

For a single rotation

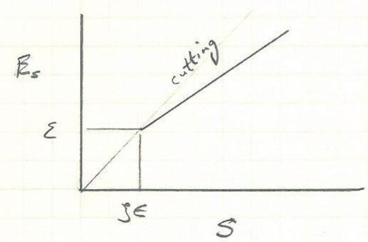
$$E = \int T\,d\theta = 2\pi T$$

$\forall = \pi r^2 \delta$; δ = depth of cut per revolution

$\delta = ROP/N$; ROP = rate of penetration
N = rotary speed

$$E_s = \frac{2\pi T}{\pi r^2 \delta} = \frac{2T}{r^2 \delta} = \frac{2T \cdot N}{r^2 \cdot ROP}$$

After Detournay & Defourny, "A Phenomenological Model for the Drilling Action of Drag Bits", at the pure cutting point, $E_s = \varepsilon \approx UCS$



Solving for the torque

$$T = \frac{r^2 \epsilon}{2}\,\delta = \frac{r^2 \epsilon}{2} \cdot \frac{RoP}{N}$$

& the delivered power is

$$P = T \cdot N$$

For Sierra White Granite, $\epsilon \simeq 28$ ksi
Assume 4"Ø bit, ROP = 30 ft/hr @ 100 rev/min

$$T = (2\,in)^2 (28 \cdot 10^3\ \#/in^2)(30\ ft/hr) / \left[2\left(100\ \tfrac{rev}{min}\right)\left(60\ \tfrac{min}{hr}\right)\right] = 280\ ft\text{-}\#$$

$$P = (280\ ft\text{-}\#)\left(100\ \tfrac{rev}{min}\right)\left(\tfrac{min}{60\,s}\right)\left(hp/550\ ft\text{-}\#/s\right)\left(\tfrac{2\pi\ rad}{rev}\right) = 5{,}3\ hp$$