



## Are You Drilling Optimized or Spinning Your Wheels?

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### Abstract

An innovative variation of a formerly time-consuming rig-site procedure is described to determine the founder point of roller-cone drill bits. If a drill bit re-drills cuttings before they are removed from the bottom of the hole, excess energy is expended resulting in less hole and faster bit wear. Regardless of the hydraulics available or the hydraulic optimization program used, this optimum operating point, or founder point, can be determined at the rig floor with little or no wasted rig time. From rig-floor measurements the best combination of WOB and RPM can be determined for a particular formation for the hydraulics available on the rig. The goal of this procedure is to drill more hole faster with fewer bits.

A new drilling rate equation is introduced which matches most published literature. This equation is used to guide calculation of the founder point. Driller's refer to the founder point as the "sweet spot" because usually the bit drills faster at that particular weight and rotary speed. The procedure presented will assist the driller's search for the sweet spot.

Field examples and interpretation techniques are included..

### Introduction

A new drilling rate equation is introduced that describes the effects of weight on bit, rotary speed and differential pressure on rate of penetration. The concept of founder (or flounder) points is revisited and a field procedure explained to determine how to measure the founder point at the rig. Application of this technique results in the maximum drilling rate possible with minimum bit wear.

### Drilling Rate Equation:

A drilling rate equation is presented which matches published data. Many years ago, Jordan and Shirley<sup>1</sup>

published a drilling rate equation, 1, that contained the now-popular "d" exponent. That equation was:

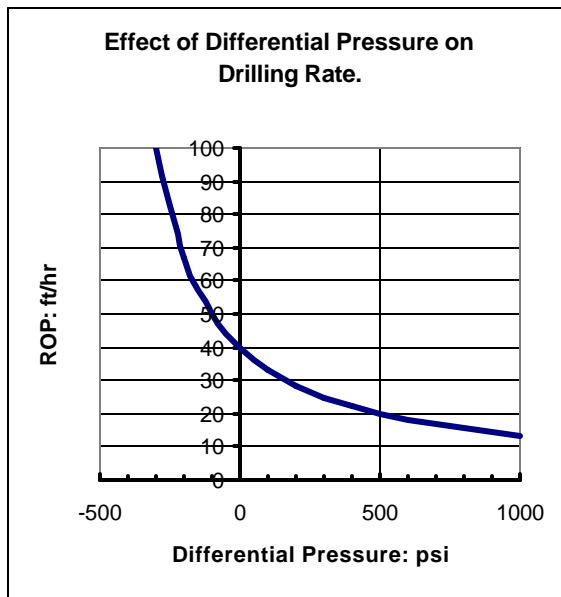
$$ROP = k W^d N. \quad \text{Eqn 1}$$

Where: ROP is the rate of penetration,  
k is the drillability of the formation.  
W is the weight on bit,  
d is the exponent for weight on bit, and  
N is the rotary speed.

If the formation doesn't change, and the mud weight, rotary speed, and weight on bit are held constant, then the rate of penetration should be constant. When drilling into abnormal pressure without changing mud weight, the pressure differential across the bottom of the hole decreases. Drillers recognize an increase in drilling rate as an indicator that the bit is penetrating formation pore pressure higher than before. If k, W, and N are constant, the ROP should be constant. When ROP increases, it was assumed that the 'd' exponent changed. Plotting the logarithm of 'd', the change in 'd' is easily observed. This makes a very effective method to indicate abnormal pressure.

From a mathematical point of view, however, any constant on the right side of equation-1 could be designated as a variable and indicate a decrease in differential at the bottom of a well bore. Since the publication of the 'd' exponent, several experiments with full size bits drilling with a pressure differential across the bottom of the hole, have identified the relationship between ROP and pressure differential for PDC, milled tooth, and insert bits. All relationships have the general form shown in Fig. 1.

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**Figure 1**  
**Effect of Differential Pressure on Drilling Rate**

This appears to be an exponential curve; but experimental data found in the literature could not be duplicated with that type of mathematical expression. Equation 2 seems to best match published data for any size drill bit:

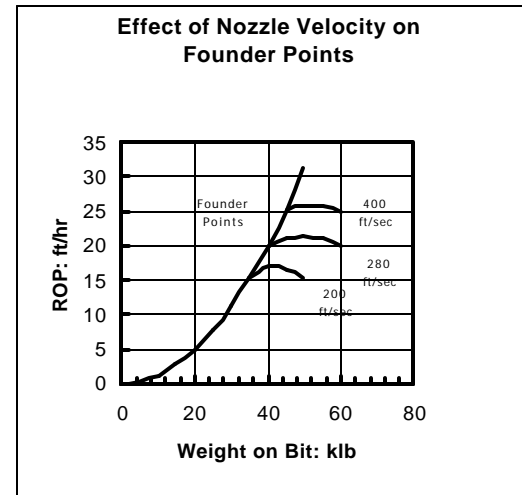
$$ROP = \frac{k W^2 N^{0.7}}{m + \Delta P} \quad \text{Eqn 2}$$

A simple reciprocal of  $(m + \Delta P)$  matches the published literature. The value of 'm' is on the order and magnitude of the tensile strengths of various rocks for the data reported. When  $\Delta P$  is equal to  $-m$ , the curve approaches infinity. Obviously the equation is a first order and magnitude approximation. However, when drilling under-balanced with milled tooth bits, high drilling rates have been achieved even after the bit is completely worn.

Equation 2 is valid up to the founder point of a drill bit. Founder points were introduced by Grant Bingham<sup>2</sup> as far back as the 1950's. A founder point indicates the bit loading that causes chips to form that cannot be removed with the available hydraulics. Obviously increasing the hydraulics (or flow rate for a particular bit) will increase the founder point. Founder points are important for field operations because it defines the point at which increasing bit loading no longer provides the proper increase in drilling rate. The bit then drills at a lower ROP than it should. In the worst cases, overloading the bit frequently balls the drill bit and the drill bit quits drilling. In most cases the bits are worn faster than they should be, resulting in bit trips that

should not be required. Saving one or more trips out and in a hole makes a large impact on economics.

Rubin Feenstra, Shell, in 1963 (SPE meeting in New Orleans) also published a paper showing how nozzle velocities affected the founder point, Figure 2. Their curve was obtained

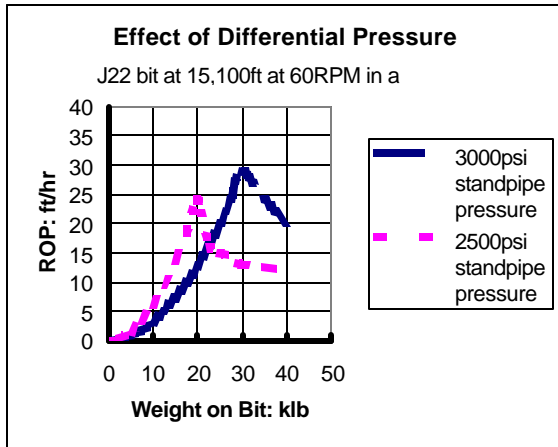


**Figure 2**  
**Founder Points**

by controlling the bottom hole pressure during experiments in the laboratory. In the field, the pressure differential across the bottom of the hole depends upon the flow rate. The pressure drop in the annulus goes up when the flow rate goes up. If the flow rate is decreased, the cuttings in the annulus may accumulate and increase bottom hole pressure because the mud weight in the annulus has increased. Pressure measurements while drilling some times can indicate poor hole cleaning capabilities. This is particularly true in high angle holes because the effect is immediate. In more vertical holes with slow drilling, the bottom hole pressure may initially decrease when the flow rate decreases; but will probably increase as the cuttings load in the annulus increases.

In a vertical well the standpipe pressure was decreased from 3000 psi to 2500psi and another drill-off test performed, Figure 3. The equivalent circulating pressure was very close to the formation pressure. The decrease in bottom hole cleaning should decrease the founder point. It did. The drilling rate below the founder point was higher for the lower standpipe pressure. With 17,000 lb bit weight, decreasing the standpipe pressure increased the drilling rate from 9.8 ft/hr to 18 ft/hr. Past the founder points, however, at 40,000lb bit weight, the rate of penetration was higher for the higher standpipe pressure (12 ft/hr compared to 20 ft/hr). Observe also that if the hydraulics were optimized and improved, this

bit could have drilled significantly faster with 30,000 lb bit weight. Calculating the projected drilling rate from the drill-off tests, at 40,000lb bit weight with adequate or better hydraulics, this bit should have been drilling at almost 100 ft/hr. With the hydraulics actually available, increasing the bit weight to 40,000 lb decreased the drilling rate. The rig was drilling with 40,000 lb bit weight before these drill-off tests were performed.



**Figure 3**  
**Field Measurements of the Effect of ECD**

**How to perform Drill-off Tests**

Founder points can be found at the rig site using drill-off tests. In 1958 Arthur Lubinski suggested timing how long it took the bit weight to drill off. With the brake locked in place, the top part of the drill string does not move. As the bit makes hole, the drill pipe stretches. Every change of 2000 lb bit weight will increase the drill string length the same amount because the pipe is elastic. Generally, the drill collars are so large that they do not stretch as much as the drill pipe and can be neglected in the calculations. The amount of stretch can be approximated by the Stretch Constants available for Stuck Pipe Calculations or it can be measured on the rig floor. Stop the rotary and mark the drill string. Apply 10,000 lb to the bit and measure the movement; apply another 10,000 lb bit weight and measure again. Average these two numbers to identify the elastic constant of the drill string.

**Procedure**

1. Select a rotary speed and a maximum weight to be applied to the bit. The maximum weight may be determined from the drill collars in the hole or the bit manufacturer’s recommendations.
2. Set the rotary speed, and apply the maximum

weight. Drill a short distance and recheck the rotary speed.

3. Lock the brake down and record the time.
4. Record the time for every 2000 lb increase in string weight (or decrease in bit weight).
5. Continue the procedure until about 25% of the original bit weight remains. Continuing to measure time in the very low bit weights uses too much rig time.
6. If significant discontinuities are observed in the data, the formation may have changed and the test needs to be repeated. – particularly in the higher bit weight range.
7. Calculate rate of penetration for each change in bit weight from the equation 3:

Eqn 3 :

$$ROP = \frac{(SC)(DP \text{ length})(\Delta WOB)}{(1000 \text{ ft})(1000 \text{ lb})} \left[ \frac{3600 \text{ sec}}{\text{hr}} \right] \left[ \frac{\text{ft}}{12 \text{ in.}} \right] \Delta T$$

where: SC is the stretch constant,  
 DP length is the drill pipe length,  
 Δ WOB is the change in bit weight for each interval, and  
 ΔT is the time, in seconds, the change bit weight.

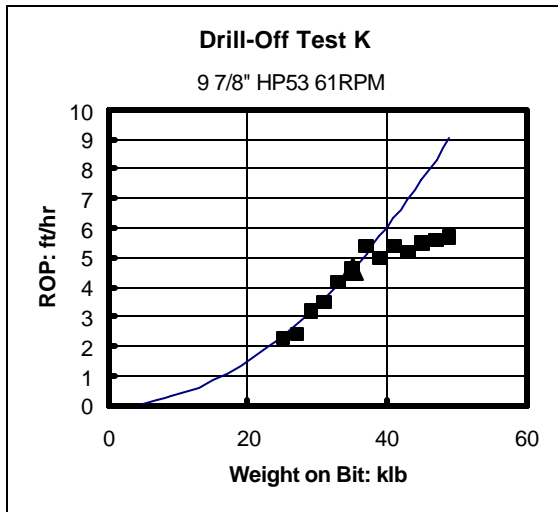
8. Plot the drill-off curve.

These calculations may be easily performed on a spread sheet like Excel or Lotus. Note the numerator of equation 3 is a constant for the tests.

**Test data.**

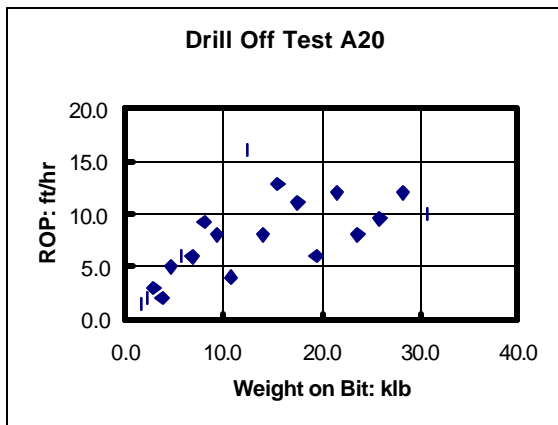
Drill-off Test K at 14,500ft indicated a founder point around 37,000 lb bit weight. The triangle data point was used to calculate the solid curve shown in Figure 4. This data indicates that the hydraulics were insufficient for the drill bit.

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**Figure 4**  
**Rig Site Drill-Off Test**

Unfortunately, not all data is as easy to interpret as Drill Off Test K. In many holes the stick-slip of the drill collars prevents the weight indicator from actually following the weight on the bit. This problem, and the corresponding erratic results, lead to the abandonment of this method many years ago. Some of the data looks like the data presented in Figure 5 from Test A20.

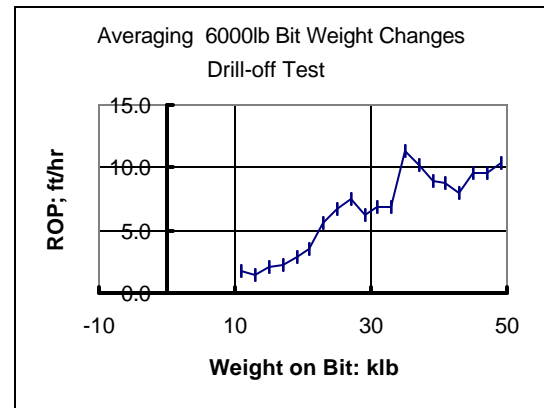


**Figure 5**  
**Typical ? Data**

Joining all of these data creates an almost incomprehensible maze. This is the reason the method was abandoned many years ago. In an attempt to determine the founder point in at the rig site, many other techniques were tried. The most popular was measuring the time required to drill 3ft at different WOB and RPM. This gave accurate information, but by the time all of the bit weights and rotary speeds were tested, the bit was dull. Selecting only five or six different combinations of WOB and RPM failed to produce a sufficient indicator of

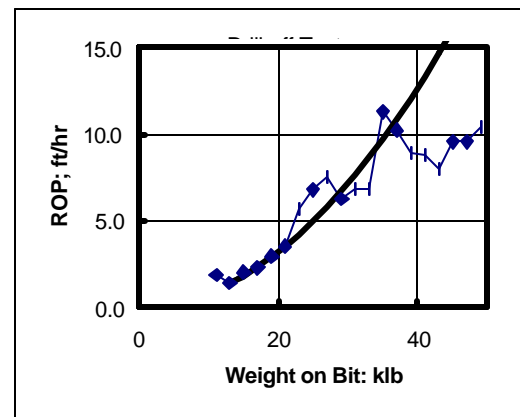
the founder point. A variety of other techniques, including measuring from squeak to squeak on the brake to stripping the drilling recorder line to the top of the traveling block. Finally, the erratic data was examined again.

Buried within the data in Figure 5, however, is the founder point. The data points to the right of 10,000 lb bit weight seem to group into some type of relatively constant value. If the reason for the irregularity is stick-slip, perhaps the time intervals for measurements are too short. This data could be analyzed by assuming that the bit weight change was 4000 lb or 6000 lb between data points. Assuming a 6000 lb change in bit weight, ROP is calculated for the change in bit weight from 50,000lb to 44,000lb and then from 48,000lb to 42,000lb. In this way no data is discarded, but the data is smoothed into something comprehensible, Figure 6.



**Figure 6**  
**Smoothing Drill-Off Data**

Since the ROP is a function of the weight on bit squared, one data point could be used in Figure 6 to calculate the theoretical curve.

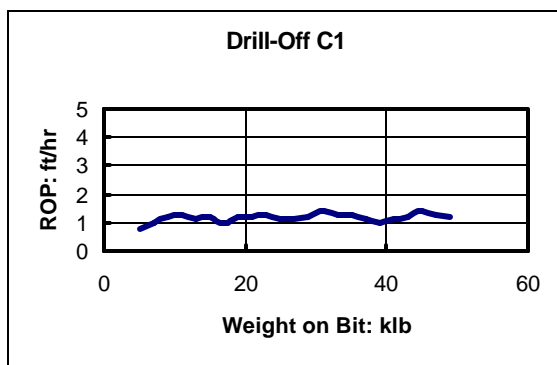


**Figure 7**  
**Comparing Drill-Off Data to a Theoretical Curve-**

The data seems “well-behaved between 21,000lb and 13,000lb, so the drilling rate at 21,000lb was used to calculate a constant of proportionality. The curve without data points in Figure 7 represents the theoretical curve. Now the irregular data seems to indicate a founder point in the range of 35,000lb bit weight. This was confirmed at the rig by comparing the drilling rate at that bit weight with the drilling rate at 45,000lb.

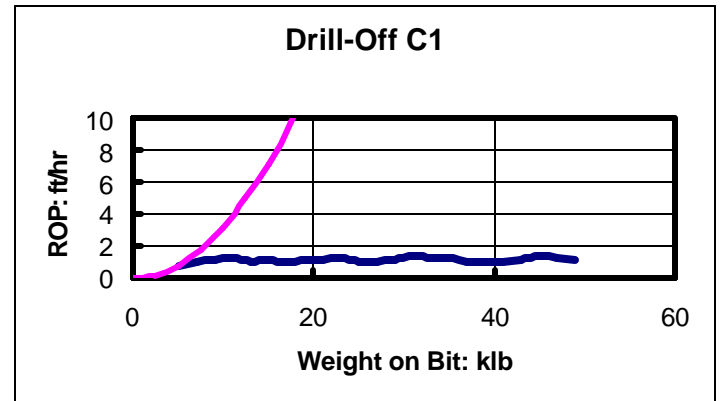
Generally, most data can be smoothed by just using a change of 4000 lb bit weight instead of 6000lb. The example in Figure 5 was the worst set of data taken in the field. By using the moving average smoothing technique, even that data could be interpreted.

Early in the development of this smoothing technique, data was acquired to validate the fact that rate of penetration was a function of the square of the weight on the bit. This required the drill-off tests to extend into the very low weight-on-bit range. Several field tests confirmed that relationship. During one of these attempts very early in the development of the technique, however, unusual drill-off data was recorded. This data seemed to indicate that the proposed technique was invalid. The drill-off test data, Figure 8, indicated that the drilling rate was independent of weight on bit.



**Figure 8**  
**Strange Drill-Off Data**

The rig supervisor indicated that the bit would be pulled the next morning because of a low penetration rate. After this drill-off test, the entire project seemed in jeopardy. Clearly, ROP was not a function of weight-on-bit squared. When the bit arrived at the surface, the reason became completely clear. The IADC 537 bit had only a few shards of inserts left on the cones. The bit foundered within the first 5000 lb bit weight. The bit should have been pulled long before the drill-off test was conducted.



**Figure 9**  
**Comparing Theoretical Curve with Dull Bit Drill-Off Data**

Assuming that the final point on the drill-off curve was the founder point, the drilling rate with 10,000 lb bit weight should have been 10 times the measured value, Figure 9.

Later, a similar set of data was observed from a small drilling rig equipped with small duplex pumps. Insufficient hydraulics can also result in low founder points. Regardless of the hydraulics available at a rig, the founder point determination can guide the way to cheaper drilling.

## Conclusions

Drill-off data from field tests can be analyzed and bit loading adjusted to prevent bit foundering. This results in drilling rates that are sometimes higher than in the foundered condition; the bits last longer; and fewer bit trips are needed.

## Nomenclature

- DP* – Differential pressure across the rock being drilled
- DT* – Time difference between WOB interval changes
- DP length* – drill pipe length
- K* – Formation drillability factor
- M* – formation strength factor
- N* – Rotary speed
- PDC* – Polycrystalline Diamond Compact (synthetic diamond bit cutting structure)
- Psi* – pounds per square inch
- ROP* – Rate of Penetration, Penetration Rate
- RPM* – Rotary speed, revolutions per minute
- SC* – Stretch Constant
- W* – Weight on bit
- WOB* – Weight on bit

**References**

1. Jorden, J.R. and O.J. Shirley, "Application of Drilling Performance Data to Overpressure Detection", JPT (1966), 1387-1394
2. Bingham, M.G., "A New Approach to Interpreting Rock Drillability", O&G Journal, Nov. 2, 1964 thru April 1965

**Appendix A: How to average time for a 2000lb, 4000lb, and a 6000lb change in bit weight**

The method of averaging data is presented below in the spread sheet format. Only a segment of the drill-off data is presented. The time of day is recorded, to the nearest second, as the weight indicator hand crosses the indicated weight-on-bit value. Subtracting the time from one weight on bit number to the next value, the time required to drill-off 2000lb is calculated in seconds. The drilling rate equation using the stretch constant evolves into a constant divided by the time to drill-off the 2000lb. In the first chart, the drilling rates are quite variable and would be difficult to interpret.

Sample Data Sheet

Weight On Bit Klb	Time of Day	Δ Time sec	ROP 834/T ft/hr
42	02:34:35		
		70	11.9
40	02:35:45		
		139	6.0
38	02:38:04		
		76	11.0
36	02:39:20		
		56	14.9
34	02:42:00		
		104	8.0
32	02:42:52		

To account for 'stick-slip', assume that the time for the bit weight to change by 4000lb is used instead of 2000lb, but calculate the drilling rate for every 2000lb change in bit weight. No data is discarded and this acts like a smoothing function.

Weight On Bit Klb	Time of Day	2klb Δ Time sec	4klb Δ Time sec	ROP for 4klb 1668/T ft/hr
42	02:34:35			
		70		
40	02:35:45		209	8.0
		139		
38	02:38:04		215	7.8
		76		
36	02:39:20		132	12.6
		56		
34	02:42:00		160	10.4
		104		

In this well, the data was still somewhat confusing, so the average time for a 6000lb change in bit weight was needed to analyze the data.

Weight On Bit Klb	Time of Day	2klb Δ Time sec	6klb Δ Time sec	ROP for 6klb
42	02:34:35			
		70		
40	02:35:45			
		139	285	8.8
38	02:38:04			
		76	271	9.2
36	02:39:20			
		56	236	10.6
34	02:42:00			
		104	212	11.8
32	02:42:52			

## FIGURES

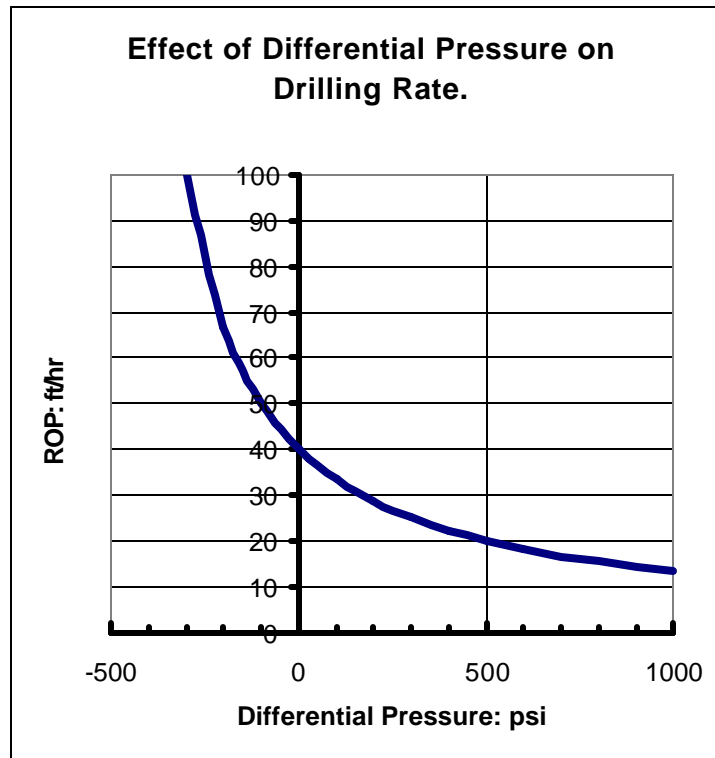


Figure 1 - Effect of Differential Pressure on Drilling Rate

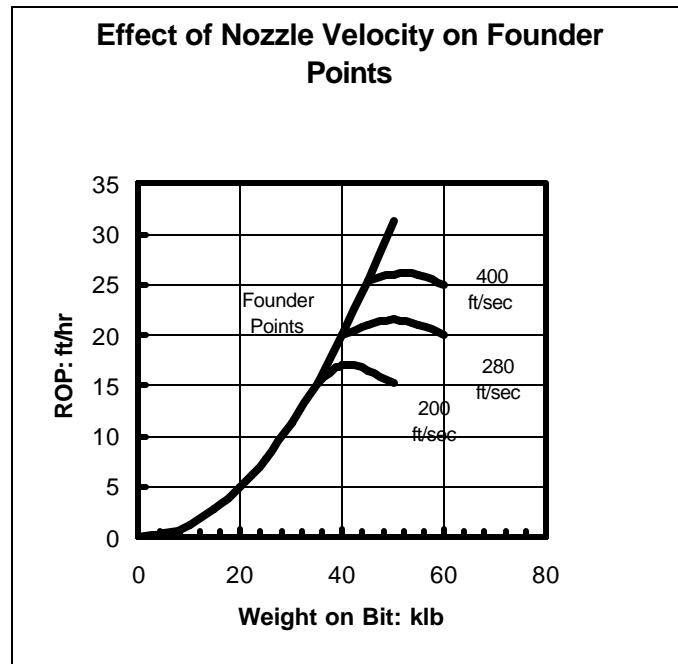


Figure 2 - Founder Points

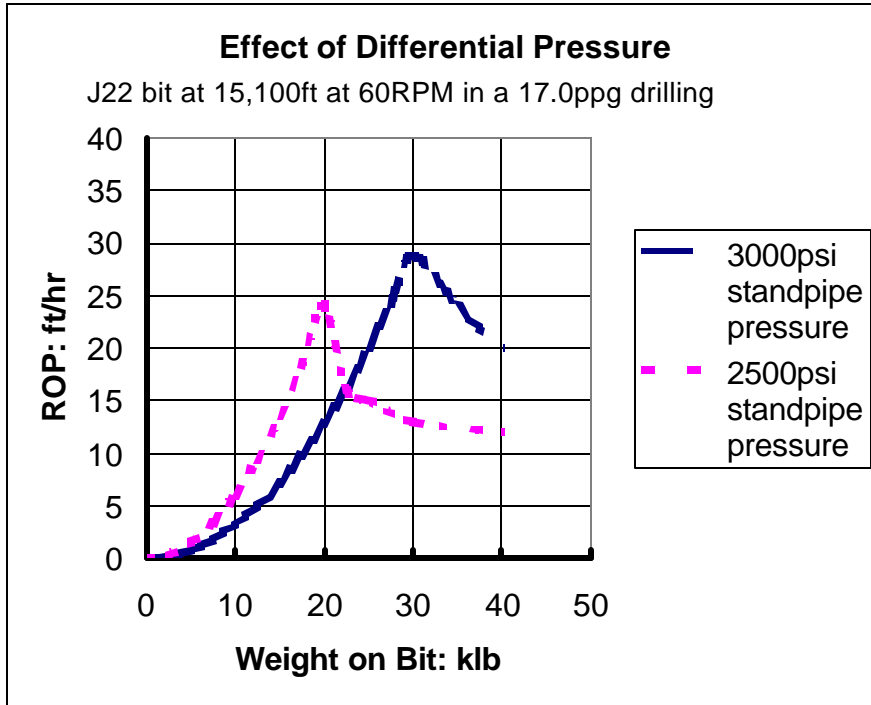


Figure 3 - Field Measurements of the Effect of ECD

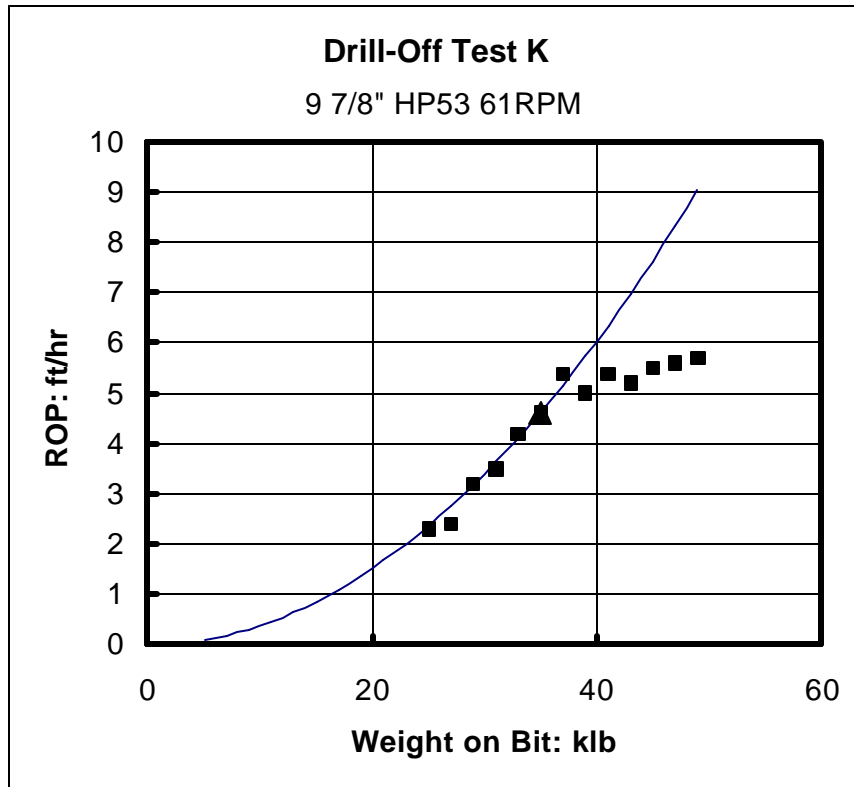


Figure 4 - Rig Site Drill-Off Test



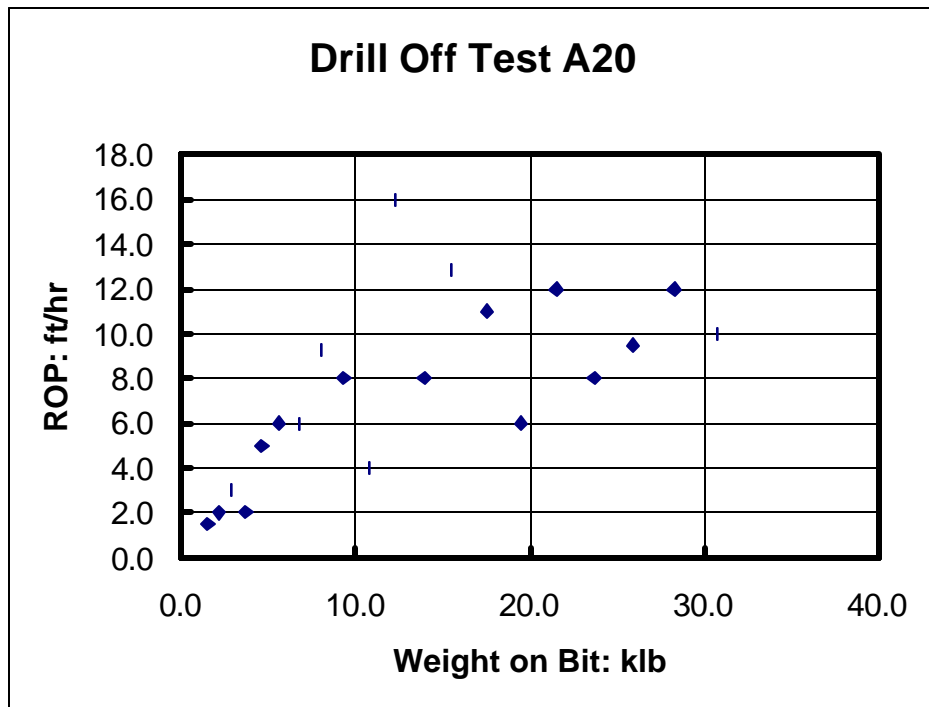
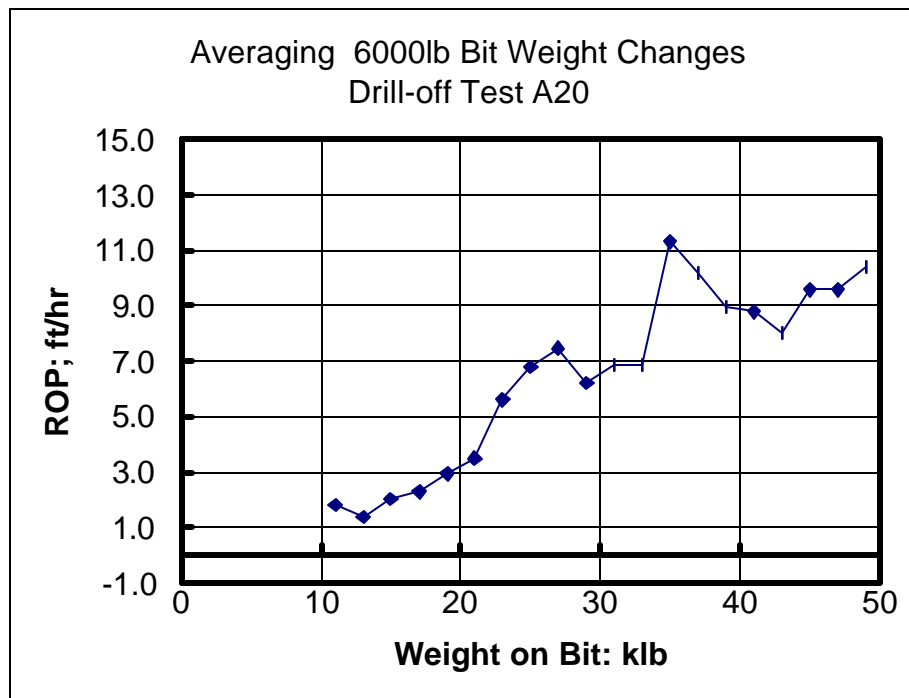
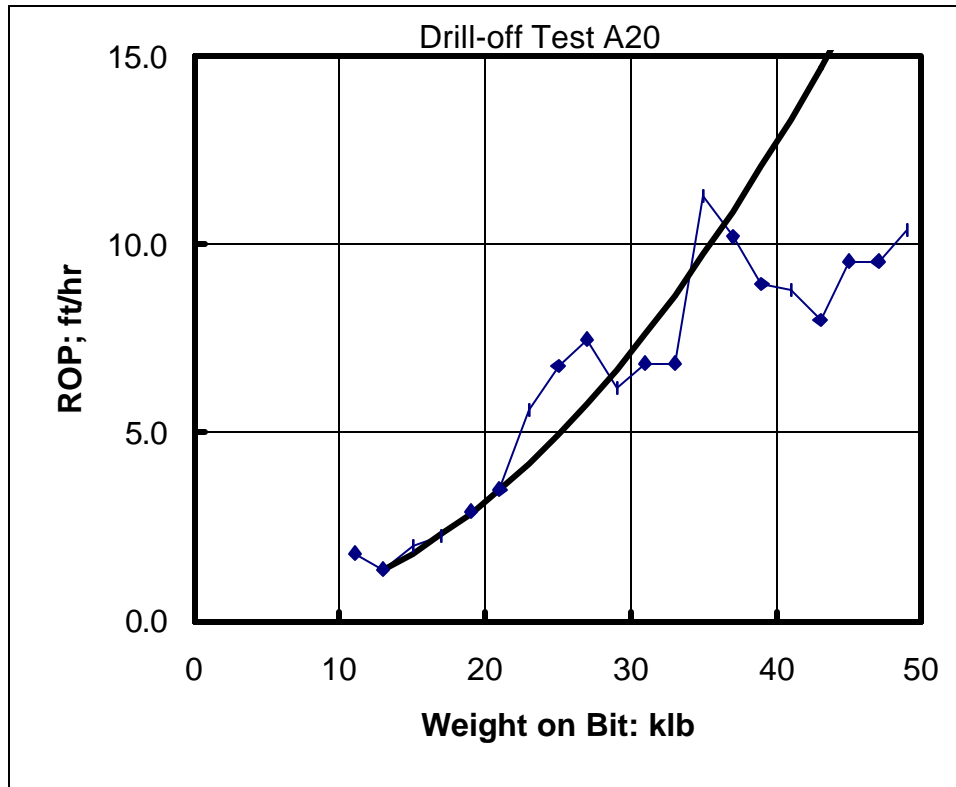
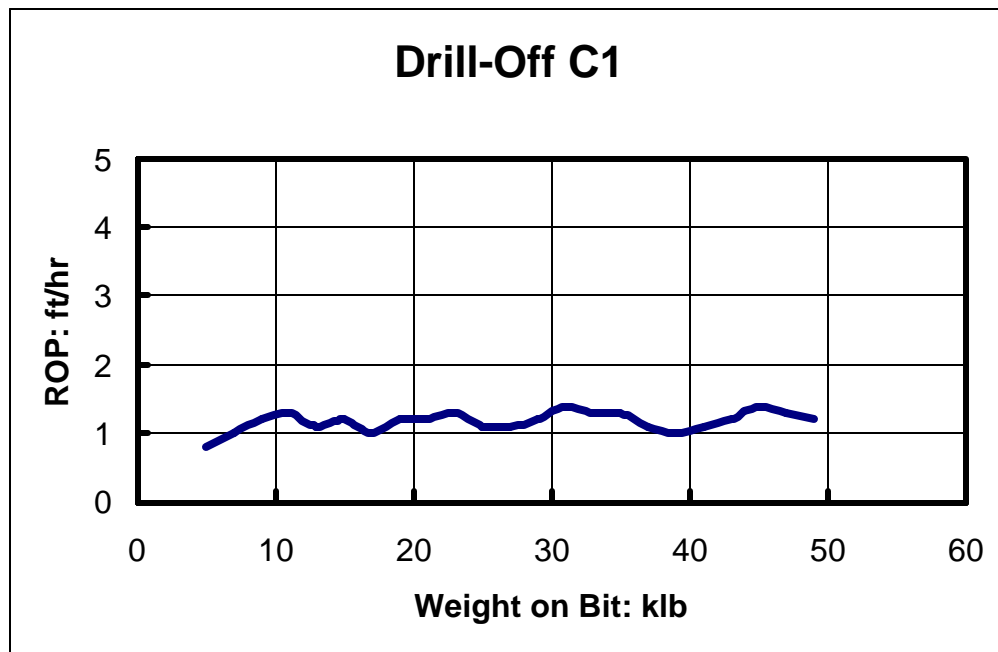


Figure 5 - Typical ? Data

Figure 6  
Smoothing Drill-Off Data



**Figure 7**  
Comparing Drill-Off Data to a Theoretical Curve-



**Figure 8 - Strange Drill-Off Data**

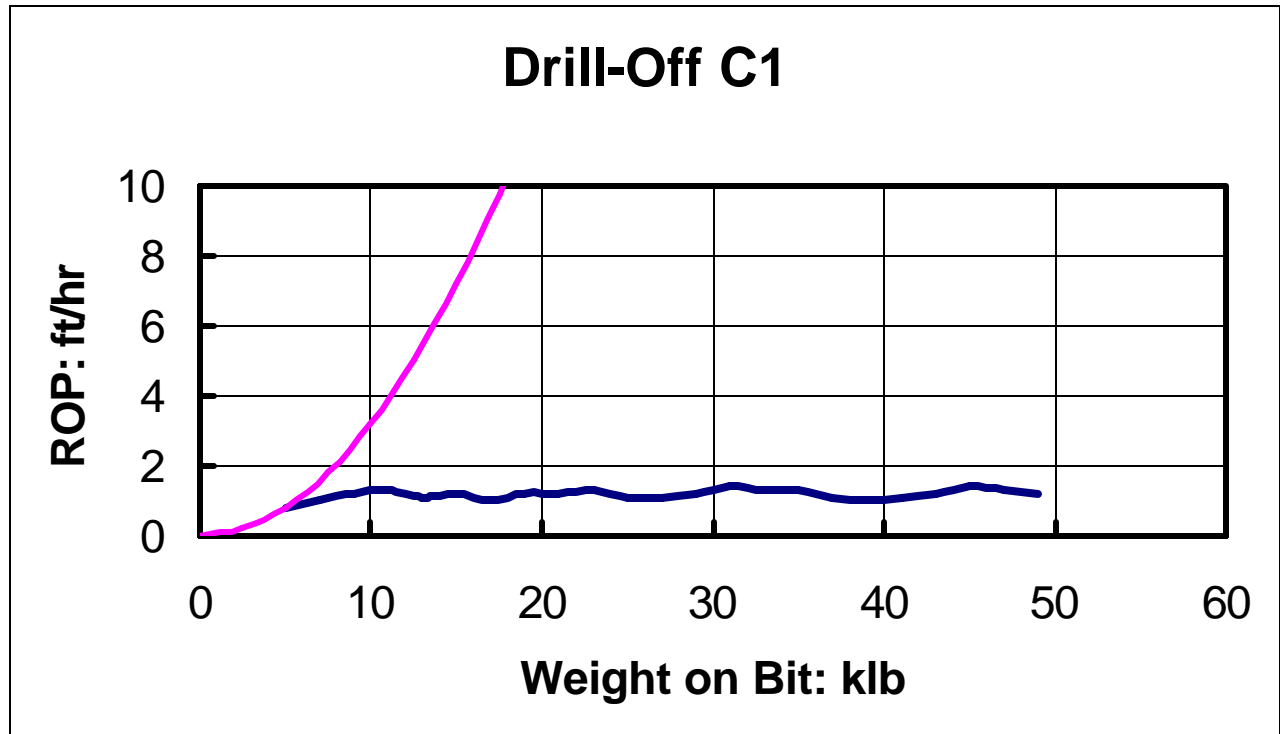


Figure 9 - Comparing Theoretical Curve with Dull Bit Drill-Off Data