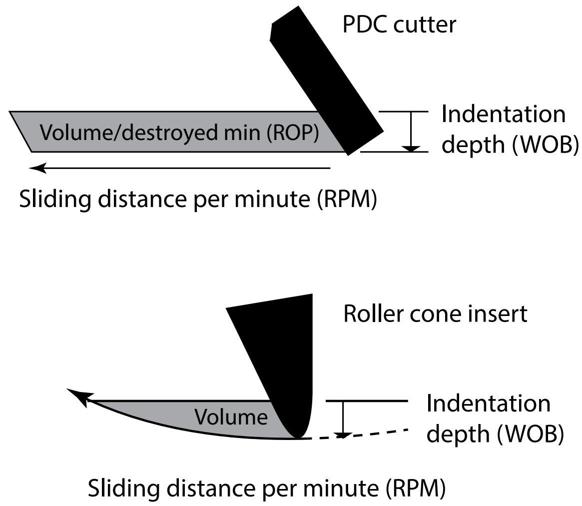
Drilling mechanics and performance

The drill rate that can be achieved with a specific bit is determined by the aggressiveness of its design, the weight on bit (WOB) applied, the rotations per minute (RPM) and the rock strength. When the RPM or WOB are increased, the rate of penetration (ROP) should increase proportionately. If the increase is proportionate, the bit is efficient. Consequently, if the ROP does not incease proportionately to WOB, it is because something is making the rock cutting process inefficient. There is a specific dysfunction causing the depth of cut to be less than it should be. When drilling data is examined closely it is clear that in much of the footage drilled the bit is not cutting efficiently and this, rather than rock hardness, is the primary cause of low rates of penetration. The causes of inefficiency are known and for each type of bit dysfunction there are steps that can be taken immediately by the driller to improve the efficiency, ROP, bit life, and borehole quality. There are also engineering redesign options, but the focus of this chapter is the actions that can be taken by the driller.



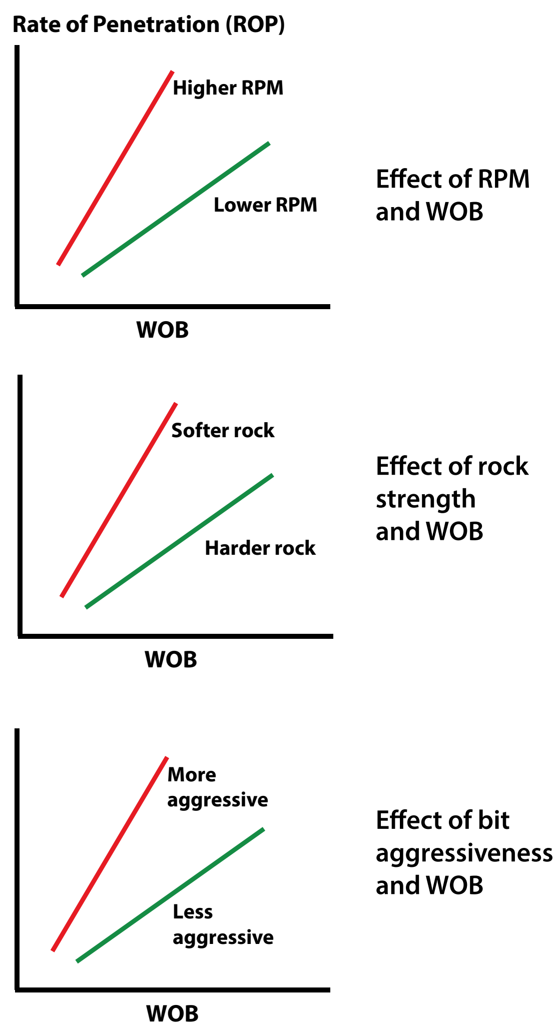
Figures DP-1a and -1b (from top): All bits essentially work in the same manner. The rock volume removed per minute is determined by indentation depth and the combined distance per minute that the cutters travel while engaged.

Bit mechanics

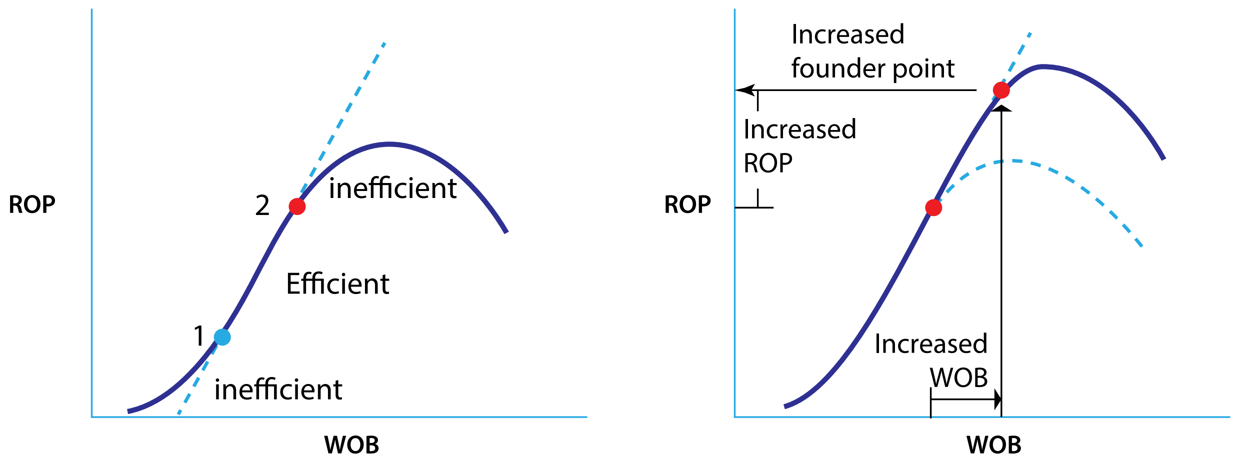
All bits drill in a very similar manner. When weight is applied, the cutting structure indents the rock to some depth, and then as the bit is rotated the rock to the right of the buried cutting structure is destroyed. Indentation depth in a given rock is determined by the WOB the driller applies and the rotating sliding distance per minute is determined by the RPM used. The volume of rock, or drill rate, is the product of both (**Figures DP-1a and -1b**). Indentation depths are not large, and most of the volume of rock removed is from rotation and the distance the cutters slide per minute. For example, the teeth of a more aggressive roller cone bit are aligned to stay on bottom and engaged for a greater distance in the rock, so they remove more rock volume per minute.

The expected responses to WOB are shown in **Figures DP-2a, -2b and -2c**. If the bit is efficient, a plot of ROP vs WOB will form a straight line, regardless of rock strength, bit cutters and design, or RPM. The straight line is referred to as a proportionate response, a term that will be used throughout this chapter.

Figures DP-2b and -2c show the effects of rock strength and bit aggressiveness. As rock strength increases, more WOB will be required to achieve a given indentation depth (depth of cut). The change in depth of cut and ROP is approximately proportionate to the change in rock strength. For example, if



Figures DP-2a, -2b, and -2c (at right, from top): If the bit is efficient, a plot of ROP vs WOB will form a straight line, regardless of rock strength, bit cutters and design, or RPM. Figure DP-2a: Effect of WOB and RPM. Figure DP-2b: Effect of rock strength. Figure DP-2c: Effect of bit aggressiveness.



Figures DP-3a, -3b (from left): shows a straight-line response of ROP to WOB, indicating an efficient bit up to the founder point. The driller must limit WOB to remain at or below the founder point. Figure DP-3b shows the result of changing real-time practices or design that elevate the founder point to a higher WOB. The WOB the driller can now apply without foundering is increased, as is the achievable ROP.

the rock strength increases by 10% the drill rate should be expected to decline by about 10%.

The bit aggressiveness determines the indentation depth and torque that will occur for a given WOB. As shown in **Figure DP-2c**, a more aggressive bit will drill faster because any given WOB will cause it to indent to a greater depth of cut (DOC) per revolution.

When operating efficiently, rock strength and bit aggressiveness effect the drill rate, but large changes in drill rate are usually due to inefficiency or dysfunction in the rock cutting process. If the bit is efficient, it is only necessary to raise the WOB or RPM in order to drill faster. If the bit is not cutting rock efficiently, the driller must identify and address the cause of dysfunction in order to significantly increase performance. The types of dysfunctions and the driller's response will be discussed.

If the increase in ROP is not proportionate to changes in WOB or RPM, something is interfering with the indentation depth. The poor response to WOB is referred to as bit founder. For example, **Figure DP-3a** shows the relationship the driller will observe between WOB and ROP for bit balling, which is one form of founder.

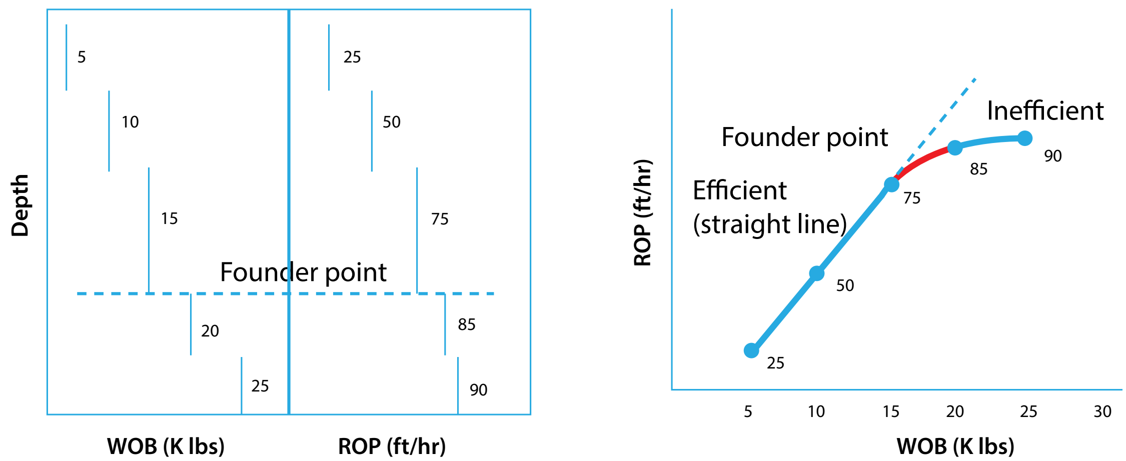
As weight is initially applied, bits tend to be inefficient at very low loads. The efficiency increases as the weight is increased. In **Figure DP-3a** the bit has reached its peak efficiency at Point 1, and a proportionate response is seen at any WOB between Point 1 and Point 2. When the bit is efficient, increased performance only requires that the driller continue to raise the WOB. Not only will the ROP increase, but it will also increase by the same amount for each incremental increase in WOB. The response is linear, proportionate and predictable. At Point 2, bit balling is beginning to occur, which interferes with the depth of cut. The bit becomes even less efficient if additional WOB is applied. Point 2 is referred to as the founder, or flounder point. The driller achieves peak performance by determining the WOB at which the bit founders and operating with a bit weight that is close to that point. The process of determining the founder WOB is repeated for various rotary speeds.

In the case of bit balling, it is also useful for the driller to conduct step tests with the third parameter that he controls, which is flow rate. Whether flow rate has any effect on performance depends on the cause of bit dysfunction, but increased flow rate is almost always effective in increasing the founder point for bit balling.

Once the driller goes through the process of identifying the founder point, parameters are used that keep the operation at or just below founder. Performance has been maximized and cannot be improved further unless the cause of inefficiency is addressed and the founder point is increased to a higher WOB.

Figure DP-3b shows what should occur to increase performance further. In the case of bit balling, for example, if pump horsepower is not already fully utilized, the driller can change the founder point by increasing the flow rate and nozzle fluid velocity. This keeps the bit clean to a higher depth of cut and drill rate. Founder will still occur, but at a higher WOB. In one field case, the founder point and achievable ROP were elevated from 120 ft/hr to 500 ft/hr with the same bit when the bit hydraulics were improved.

It might not be necessary for the driller to know why the bit is foundering to find the best current operating parameters. However, it is necessary to know the cause of founder in order to take the specific action required to significantly



Figures DP-4a and -4b (from left): In Figure DP-4a, : WOB is increased in 5,000-lb steps, and ROP responds by increasing 25 ft/hr with each step, up to 20,000 lb. Between 15,000-20,000 lb the bit founders, and the next increase in ROP is less than 25 ft/hr (10 ft/hr). If the driller were to plot the average ROP at each WOB from the test in Figure DP-4a, it would produce the curve shown in Figure DP-4b. Founder is the point at which the data is no longer a straight line (non-linear response).

improve the current limitations. For example, increasing the nozzle velocity will not improve performance if drillstring vibrations are causing bit inefficiency. Therefore, the driller must have the knowledge and ability to determine the root cause. The drill team's ability to identify the root causes of rock-cutting dysfunction in real time has been greatly enhanced by the digital data now collected and the manner in which it is processed and displayed on many rigs. There are specific actions the driller can take to improve bit efficiency for every cause of dysfunction, and many other design changes that can be made by engineering.

Testing bit performance

Most performance tests take the form of some type of step test. An example step test for determining inefficiency is shown in **Figure DP-4a**. In this case, the driller increases the WOB by 5,000 lb and the drill rate increases by 25 ft/hr. If the bit is efficient, the next 5,000 lb should yield another 25 ft/hr increase. If the drill rate increases by less than 25 ft/hr after the next step in WOB, the response is not proportionate. The increased weight has caused some form of rock cutting dysfunction (founder). While the drill rate has still increased, the bit has become less efficient. ROP will usually increase with WOB, but if the increase is not proportionate, something is wrong. The drilling performance is less than it should be, and the dysfunction might also be damaging to the bit. The same step test process can be applied when changing RPM. Increase RPM in fixed steps (i.e., 5 rpm), and ROP should increase proportionately and by the same amount with each step.

As long as a proportionate response is seen from step to step, increased performance only requires that the driller continue to increase WOB or RPM to drill faster, and also to avoid damaging the bit or BHA. It is important that each step in WOB or RPM be exactly the same. If the bit is efficient, a proportionate response will yield exactly the same increase in ROP, which is easy to see. If the steps are not exactly the same, the data can still be used, but the driller must physically plot the ROP to see if the response plots as a straight line, as shown in **Figure DP-4b**. Using identical steps eliminates the need for plotting; it is only necessary to see that the ROP change is the same with each fixed step in WOB to know that the response is proportionate (straight line).

If a downhole motor is being used, the same WOB step tests are conducted, but the motor differential pressure may also be used to observe a proportionate response, rather than just ROP. If the differential rises proportionately with each increase in WOB, the bit is efficient. If the pressure response is less than proportionate, the rock-cutting process is becoming inefficient.

Drill-off testing is a method developed in the 1950s to minimize the time to determine performance at various WOBs (**Figure DP-5**). The process works well with roller cone bits at moderate to low drill rates, but it tends to be less effective with PDC bits. The driller applies a high WOB, locks the top-drive position, and continues rotation. The rotating bit drills ahead and the locked string elongates, transferring the drillstring weight that had been applied to the bit back to the hook. The amount of drillstring elongation is called "stretch". The rate at which the hookload increases then provides an indication of how fast the string is elongating, which is also the bit drill rate .

In the following example, the driller is recording the time required for each additional 3,000-lb increase in hookload to occur, which corresponds to a 3,000-lb decrease in bit load. The ROP can be calculated and plotted during each incre-

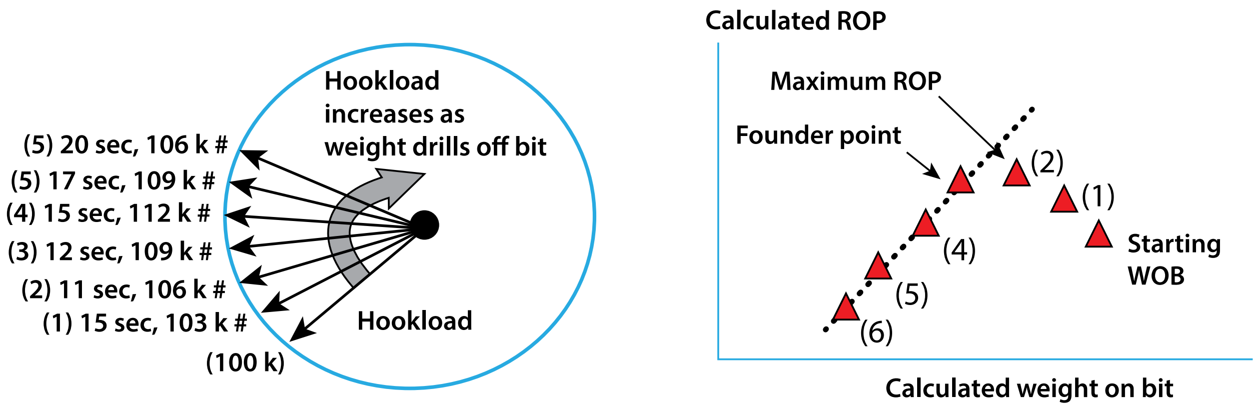


Figure DP-5: Drill-off test conducted by observing the time required to drill off 3,000-lb increments of weight on bit. The highest ROP occurs at the WOB corresponding to the shortest required time per increment.

ment by the string stretch equation shown below. Stretch constants for API DP may be found in reference manuals.

DP Stretch
= (Stretch Constant for specific DP)*(DP Length) *(Step Change in WOB) **Eq 1**

Where units are:
DP Stretch, in.;
Stretch Constant, (in./k lb)/k-ft;
DP Length, k ft; Step Change, k lb

"k" indicates thousands

ROP = (DP Stretch/Time)*[(3,600 sec/hr)/12 in./ft)

Where units are:
ROP, ft/hr;
DP Stretch, in.;
Time, sec

The advantage of plotting data is to document the results and allow it to be communicated offsite. If documentation is not needed, drillers usually conduct the test by simply observing the time required for each increment of weight to drill off and then using the WOB corresponding to the fastest time. In this example, the fastest drill rate would be seen at a WOB corresponding to the 11- or 12-sec drill-offs (positions number 2 and 3 in **Figure DP-5**).

Mechanical Specific Energy (MSE) surveillance is another method for determining drilling performance. Drill-off tests are well suited to roller-cone bits, intermediate drill string lengths with significant stored stretch, and bit balling. But the procedure does not produce clear results with PDC bits that drill with very light WOB, because the weight may drill off before meaningful data can be collected. Also, complex vibrations tend to dominate bit dysfunction with PDC bits. For these reasons, surveillance practices have been developed in recent years to continuously plot the amount of work the bit is doing, and this value shows whether the bit is becoming more or less efficient as changes are made in parameters.

Mechanical Specific Energy is the work or energy being used per volume of rock drilled. MSE is plotted by the data-acquisition computer alongside other drilling data, such as WOB, RPM and ROP. In theory, if the bit is perfectly efficient, the value of the MSE equals the rock strength in psi. But in field practice, it is primarily used as a relative indicator and it is not necessary to know the rock strength. The driller makes a change and observes the MSE to see if rock cutting efficiency improved or declines.

Figure DP-6 shows an MSE curve from a well in which bit balling is occurring. The footage where the MSE is high indicates that there is dysfunction (in this case, bit balling). When the bit drilled from a shale back into a sand, the MSE fell, indicating the bit's cutting structure has cleaned up and is now operating efficiently. Changes in rock hardness also affect the energy required, but this is minor when compared to the energy increase when bit dysfunction occurs, so these large changes in MSE are very useful in showing dysfunction. When combined with other information, it can also be used to determine the cause of the problem.

Chasgnes in MSE can be related to effects of dysfunction shown in **Figure DP-7**. If the MSE increases when a change is made, the performance is moving further way from the efficient performance, which would be the dashed blue line. If it decreases, the performance is moving closer to the dashed line. For example, the curve for whirl shows that if WOB is increased, the ROP performance moves closer to the predicted line, which means that inefficiency due to whirl is decreasing, and we would expect the MSE to go down. This is used as a

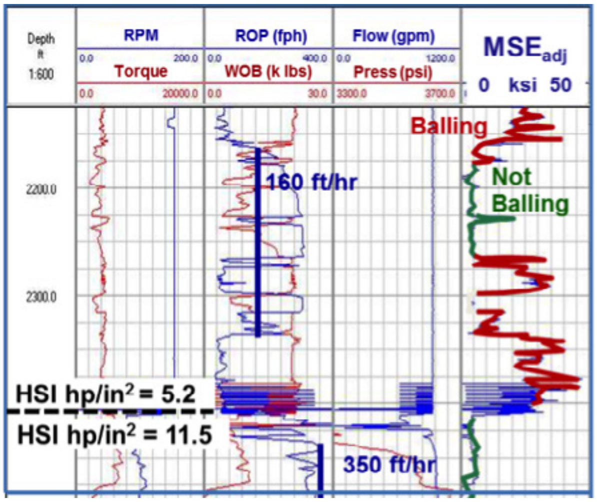


Figure DP-6: Example Mechanical Specific Energy (MSE) plot showing severe bit dysfunction in shales due to bit balling and efficient drilling in sands. Nozzles were changed during a trip to increase bit cleaning and the MSE curve now shows both shales and sands drilling efficiently.

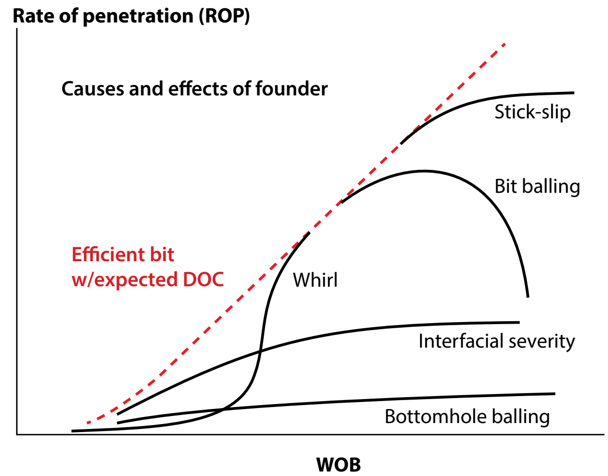


Figure DP-7: Founder, or rock-cutting dysfunction, causes the depth of cut and ROP to be less than it should be for a given WOB, causing performance to decline. The order in which the various dysfunctions are seen as WOB is increased will vary and must be determined by the driller in an organized step test.

diagnostic. If the WOB is increased, and the MSE declines, we know that whirl was the cause of dysfunction to start with. As shown in **Figure DP-7**, there is no other dysfunction that improves as WOB is increased (e.g., moves closer to the dashed line). In order to identify some of the other forms of founder, it is necessary to observe additional data, or to have more information about the drilling conditions. This is discussed in the sections below.

Regardless of the cause of dysfunction, the manner in which the driller uses the MSE to maximize real time performance is the same. To get this performance, the driller must conduct step tests by changing one parameter at a time (WOB, RPM or GPM).

- If the MSE declines the dysfunction is getting better and performance is improving. Continue with more of the same change (i.e., even higher WOB);
- If the MSE increases, the dysfunction is becoming worse and performance is declining. Change the parameter in the other direction (i.e., reduce the WOB);
- If the MSE stays the same performance is on the straight line portion of the drill off curve in **Figure DP-3a.** Continue increasing WOB to founder.

It should be emphasized that the driller cannot simply observe the MSE curve and diagnose most root causes, or determine the next action. Step tests must be conducted, and the MSE response to the change observed. It is the response that is diagnostic.

Causes of drilling dysfunctions

Each of the categories of bit dysfunction will be discussed, as well as the observations that can be made to diagnose what is occurring in real time. The corrective actions that can be taken immediately at the rig site will also be discussed. **Figure DP-7** shows the effect that each of the major forms of dysfunction may have on ROP as WOB is increased. At any given point in time only one of these usually dominates. However, this is not always true and that can complicate diagnosis. The types of rock cutting dysfunction discussed are:

- Bit balling: buildup of material on the bit that interferes with depth of cut;
- Interfacial severity: formations with hard inclusions or layers that cause axial shocks and break cutters;
- Bottomhole balling: layer of ground cuttings held to the bottom of the hole by differential pressure;
- Whirl vibrations: lateral motion of the string and bit;
- Stick-slip vibrations: torsional motion in which the bit speed oscillates periodically;
- Axial vibrations: axial motion in which the bit depth of cut oscillates periodically.

The flow chart in **Figure DP-8** summarizes a progression of activities to maximize performance. There are five forms of dysfunction shown and the driller's response to each. There are also numerous engineering redesign options, but these are not within the scope of the chapter. The flow chart is not self-explanatory and the dysfunctions, testing procedures and responses are contained in the detailed discussions to follow.

Bit balling

Bit balling occurs when drilled material accumulates on the cutting structure that begins to carry some of the applied WOB, so that the weight on the cutter tips is reduced. Con-

