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Optimizing drilling operation by correlating Mechanical specific energy & in-situ rock's compressive strength.

Abstract

Cost to drill a well is dominated by the rate of penetration (ROP) and it becomes extremely important with increasing depth. Interpreting the decrease in ROP in terms of bit wear, drilling parameters and rock strength is very crucial. This work evaluates the utility of Mechanical Specific Energy (MSE) in conjunction with drilling and rock strength parameters to maximize ROP and hence reduce the drilling times.

MSE is the measure of total amount of energy input into the drillstring divided by the volume of rock removed. The MSE and confined compressive strength(CCS) concept together describes the amount of energy used for drilling for a given volume of rock – hence the interval of inefficient bit operation can be detected. Total energy used for drilling is defined in terms of MSE; accordingly, the minimum MSE values and maximum ROP values can be recommended.

First step in the workflow involves estimation of CCS by constructing Mechanical Earth Models (MEM) at offset wells. In the second step MSE is calculated by integrating drilling parameters. In ideal situation bit efficiency is maximum when the specific energy is nearly equal to CCS. Offset well analysis provides a tentative ROP range and an expected MSE for different formations drilled. Based on this information, formations are characterized in terms of their drillability and associated problems. This methodology helps us to optimize the ROP at maximum drilling efficiency, reduce number of trips and improve the bit designs.

On observing deviations of MSE estimated in real time from the synthetic projections, raised flags to investigate if energy was diverted from drilling, or restricted extraneously. A case study from Kutch Saurashtra basin has been taken for analysis. MSE and rock strength parameters helped in interpretation by highlighting inefficiencies more clearly and faster than the interpretation of multiple data channels. This analysis assisted in identifying the primary reason for low ROP was bit wear in real time. On pull out of the hole, recommendation of bit change was validated. Post-drill analysis assisted in developing a better understanding of drillability of different bit types used (PDC and TCR).

Utilizing this concept, optimization of ongoing and future drilling operations is being done which will directly translate into the profitability of the project.

Introduction

As companies continue to expand their drilling operations within existing oil and gas fields across the world, they are more focused on to maximize profitability by optimizing drilling operations to reduce the associated costs. The concept of MSE used in drilling operations, is a progressive process that helps to indicate the inefficiency in the system. Again MSE is the measure of the amount of energy input required to remove a unit volume of rock, expressed in units of energy input divided by volume removed. It can be expressed mathematically in terms of controllable parameters; weight on bit, torque, rate of penetration (ROP), and rotations per minute (RPM). It is well documented that minimizing MSE by optimizing controllable factors results in maximum rate of penetration.
To optimize drilling in planned wells, it is important to understand problems encountered in offset wells of the field. It is important to analyze the effect of drilling parameters and equipment specifications on drilling performance. Knowing when inadequate equipment and operational parameters are being implemented in the drilling procedure as well as avoiding their use aids in the process.

Often in heavily produced fields the drilling process has become a standard routine procedure, especially on land. Process begins with an accurate understanding of the lithological characteristics encountered in the wellbore by means rock mechanical parameters like CCS. 1D-Mechanical Earth Model (MEM) workflows are adopted to estimate these parameters post calibration with available drilling and petrophysical data.

The scope of this paper is to integrate all drilling parameters with in-situ rock strength parameters to understand the drilling efficiency.

Estimation of MSE and In-situ rock strength

MSE is defined as Energy-In divided by Volume-out. Volume of a drill hole is simply cross-sectional area multiplied by depth of penetration (Δh), and work energy can be described as force multiplied by distance. in drilling operation there are two forces acting on the bit; weight on bit (axial force) and torque (rotational force). These are additive to MSE, so there are two terms in the MSE equation.

$$MSE = \frac{\text{Vertical Energy Input}}{\text{Volume Removed}} + \frac{\text{Rotational Energy Input}}{\text{Volume Removed}} = \frac{WOB * \Delta h}{Area * \Delta h} + \frac{Torque*2\pi*RPM}{Area * \Delta h}$$

The distance travelled by the bit (Δh) during a given interval is the penetration per time (ROP) divided by rotation per time. This is also known as depth of cut or as penetration per revolution.

$$\Delta h = \frac{\text{Penetration per minute}}{RPM} = \frac{ROP}{RPM}$$

Therefore, the MSE equation can be modified as

$$MSE = \frac{WOB}{Area} + \frac{Torque*2\pi*RPM}{Area * ROP}$$

A robust technique of MEM construction has been utilized estimate unconfined compressive strength (UCS) and CCS. Many empirical equations based on different petrophysical parameters like sonic, density, porosity are available in the literature to derive UCS and CCS. MEM workflow involves a critical step of history matching wherein UCS is constrained as per rock actual behavior. Once the UCS is estimated CCS which is the downhole in-situ strength of the rock is estimated using following equation:

$$CCS = UCS + DP + 2DP*SinFA/(1 - SinFA)$$

Where, MSE = Mechanical Specific Energy (psi), WOB = Weight On Bit (lb), RPM = Rotation per Minute, Torque = Rotational Torque (in-lb), Area = Cross sectional area of bit (in^2), ROP = Rate of Penetration (in/hr), P = Penetration per Revolution (in/rev), DP = differential pressure (or confining stress on the rock) in psi and FA = internal angle of friction of the rock or friction angle.

Concept of efficiency has been added to this equation, accordingly the minimum specific energy (E_{SMIN}) can be defined as the specific energy (Es) when reduced to nearly equal to the compressive strength of the rock being drilled, such that when 100% efficient.

$$E_s = E_{SMIN} \approx \text{Rock Strength } (\sigma)$$

After the concept of the mechanical specific energy was proposed, it has been used to evaluate the drilling efficiency and bit performance. According to the theory, Es is equal to the Rock's compressive strength at perfect efficiency, but the energy for crushing rock is not sufficient when Es is much greater than 'σ'. The main reasons for this phenomenon are improper drilling operation parameters or drilling problems such as bit balling, vibrations, bit dulling, and bottom-hole balling.

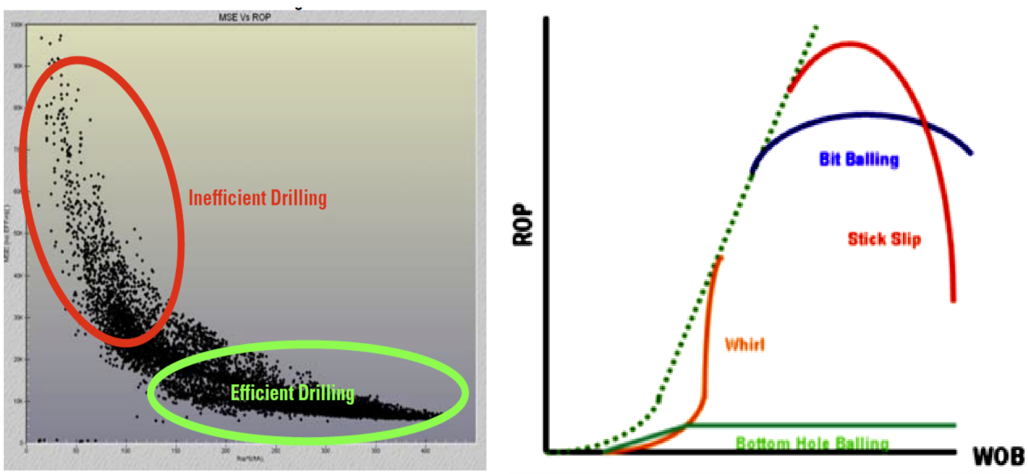
At perfect efficiency, MSE equals in-situ rock compressive strength. However, bits tend to transfer 30 - 40% of their input energy into the rock destruction process, even when operating at peak performance.

By observing any change to the minimum value of MSE, whether defined prior to the job (MSE_{min}, UCS, etc) or from real time data trends and interpretation can be made as to the efficiency of the drilling process compared to the expected.

Ideal Case Examples:

This L shaped response of MSE shown below (**Figure 1A**) is due to the mechanics of cutting, and is directly related to depth of cut. Small depth of cut is associated with grinding and high friction forces, resulting in high MSE and low Rate of Penetration.

As depth of cut increases, cutting behavior changes from scraping and grinding to fracture and breakage of rock. Higher depth of cut causes chipping and breakage of material in larger pieces, with less reduction to smaller pieces through regrinding, resulting in lower MSE because of the more efficient volume removal.
As shown in **Figure 1B** the drill off curves accounting 4 main bit performance limitations.



(A) (B)

Figure 1: (A) MSE Vs ROP curve (B) Notional representation of ROP Vs WOB Drill off Curve.

Real Case studies

Case Study 1: A deep well-XY1 drilled in Kutch Saurashtra region is analyzed having varied lithofacies in terms of their geology and petrophysical properties. Above discussed workflow has been applied and an attempt has been made to understand the formation behavior. Based on the responses in MSE, UCS and other drilling parameters a crossplot is prepared (**Figure 2**) and subsequently divided into four regions, viz. A, B, C & D.

Region A in the log plot is from a section of hole that was drilled in the same manner as the offsets field. The interval was drilled with PDC with Mud Motor, 10-20klbs WOB and water-based mud. The formations mainly Shales had rock compressive strengths of average 8 Ksi. The bit had 5 nozzles with 16/32" of TFA 0.982 in2 and drilled initially with an average ROP 10 ft/hr. But due to the high energy consumption with an MSE more than 100ksi in Shale towards end of the region, it was concluded that the bit was balled thus pulled out of hole. Later when graded the bit at surface, it was proved that the bit was balled up.

Region B: The replacement bit was almost identical in design, but was new bit with 10 nozzles of same TFA of previous one to revise the hydraulics also to improve the efficiency of bit. The revision in hydraulics enabled the cutting structure to remain clean at much higher ROP / less MSE. The MSE after the change in hydraulics was observed to approximately equal or slightly higher to the rock compressive strength, indicating that the cutting structure was clean on shales which gave average ROP 22 ft/hr at the beginning. The WOB could have been increased little more to maintain ROP at the beginning of the region B as the rock compressive strength and MSE were seen matching and no noticeable deviation as in Region A. At the beginning of the interval B, the MSE baseline was around 50ksi with frequent spikes of up to 100ksi. The spikes were believed to be due to the tendency of the bit in use to develop a whirling pattern and vibrate when drilling interbedded stratigraphy. The WOB would have been increased and the RPM would have been reduced to mitigate the whirl that would have given better ROP.

Region C shows the onset of severe whirl when an aggressive PDC bit encountered a short interval in which the formation changes with increase in compressive strength from around 8 ksi to 12 ksi (Hard stringer). The MSE increased by over 100 ksi, but not much visible increase in surface Torque was seen to supplement Stick-slip. The crew raised the WOB to try to maintain ROP, and wouldn't achieve any improvement in ROP. It was evident from the UCS that the decrease in ROP or increase in MSE is due the hard stringer and not due to any Bit dulling hence drilling was continued.

Region D towards end is believed to be a characteristic of bit dulling. The 8 ½" bit was drilling ~12ksi rock, MSE is elevated to a very high level of 200ksi. Occasional spikes in Torque associated with MSE would imply the fact that BHA was experiencing Torsional vibration eventually resulted in bit dulling. When bits dull, the energy consumption tends to increase steadily over the next 50 – 100ft.

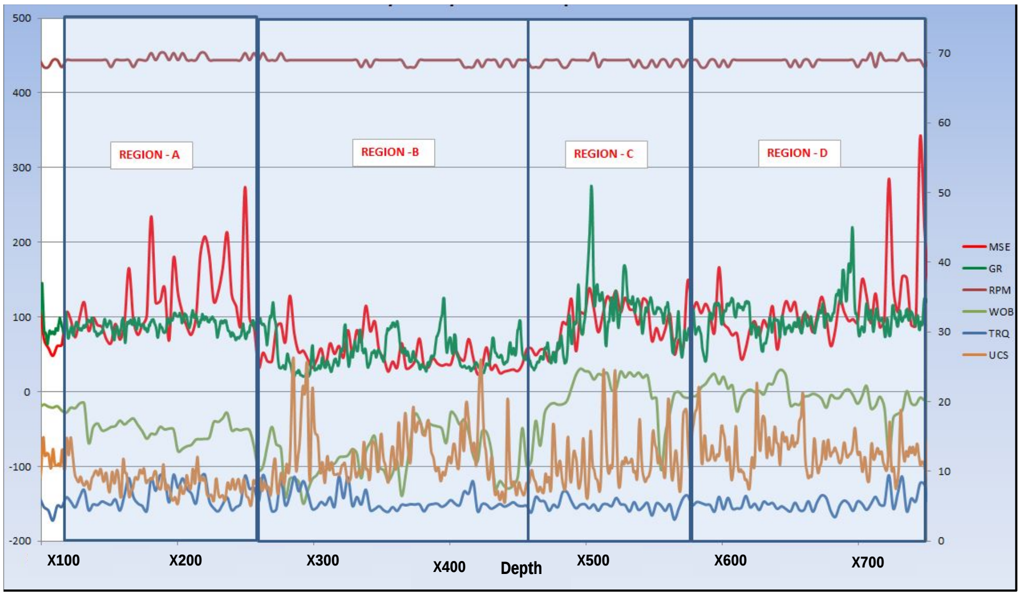


Figure 2: Post drill analysis of drilling data for well-XY-1

Other Key Findings: Different bit types including TCR and PDC with different cofiguration has been used in the well. **Figure 3 and Figure 4** shows the variation of MSE, rock strength and other petrophysical properties inside Trap Formation (primarily Basalt) and Mesozoics (Mainly Sandstone, Shale and Basaltic Inrtusions). Following points summarize the key findings:

- Thin lamination of weathered and intact trap is present in the top part of the Formation. Probably that is why energy consumed is little higher with PDC bit.
- Usage of TCR bit reduced the ROP and increased the energy consumption as reflected in increase in MSE.
- PDC gave better performance in Trap Formation as compared to TCR bits. MSE/UCS separation in the TCR drilled zone is higher as compared to PDC drilled zone **(Figure 4)**
- Delta (Difference of CCS and MSE) have inverse relation with ROP (**Figure 5**)

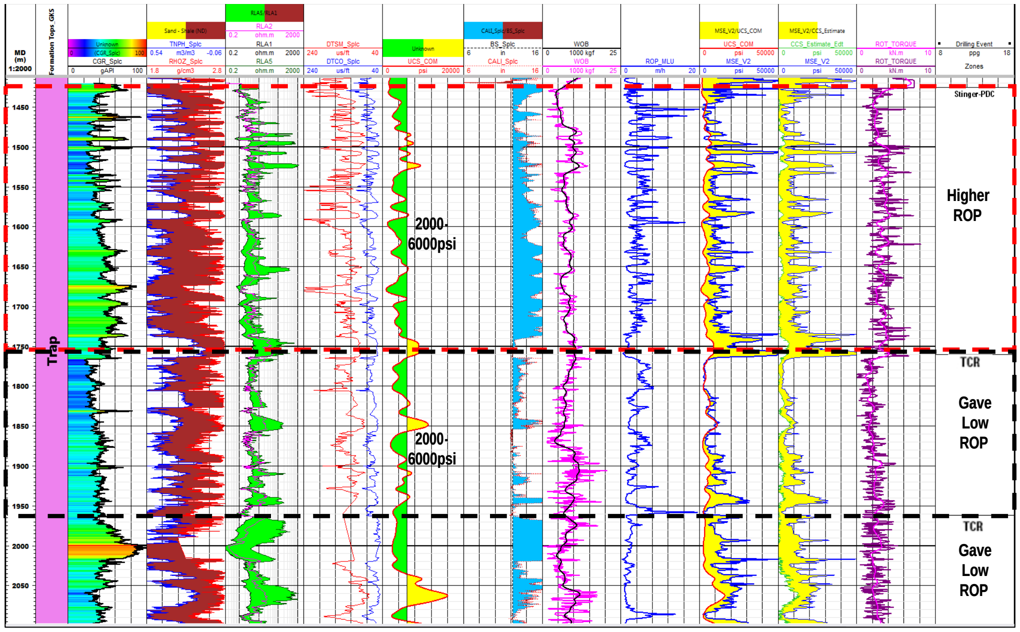


Figure 3: Understanding the Bit Performance with MSE and petrophysical evaluation in Trap Formation for Well-XY-1

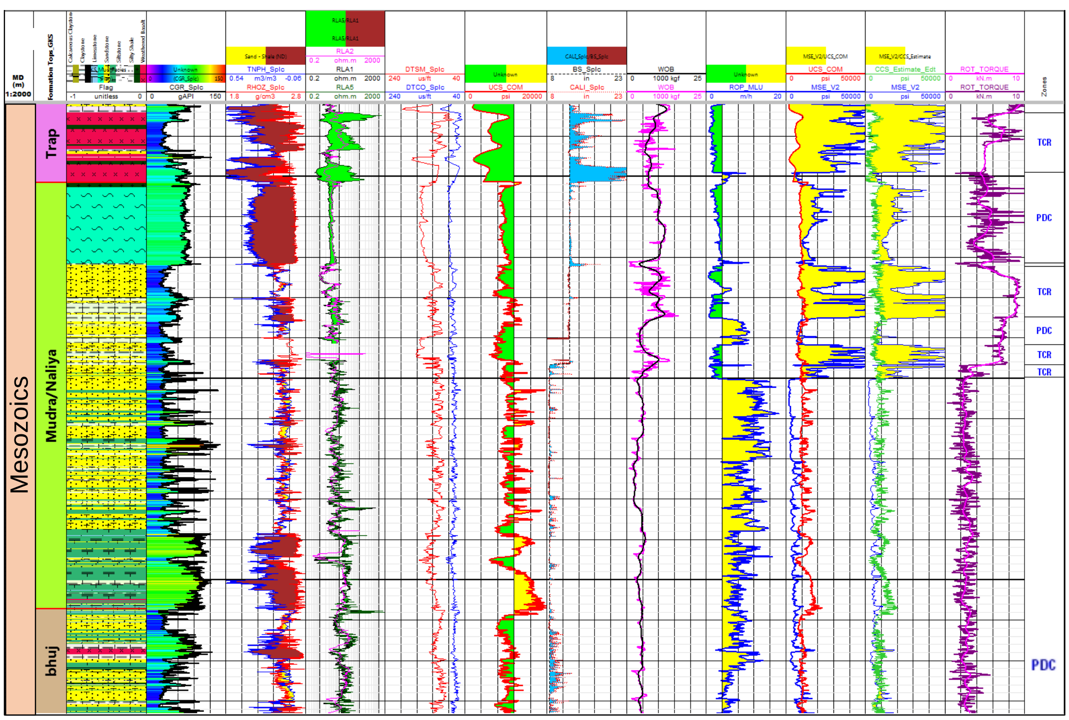


Figure 4: Understanding the Bit Performance with MSE and petrophysical evaluation in Mesozoics Formations for Well-XY-1

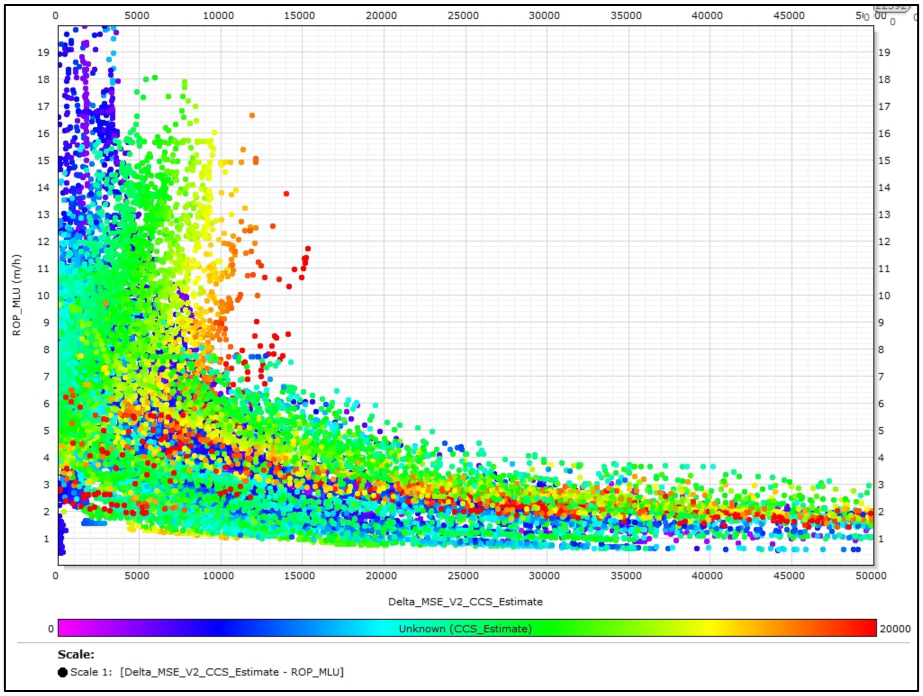


Figure 5: Crossplot between Delta (Difference of CCS and MSE) v/s ROP

Second Case Study: Another well-XZ1 from the nearby area is analyzed (**Figure 6**) with similar workflow and following key observations are found:

- Change in MSE responds to the change in the formation as increase in MSE corresponds to increase in formation density / rock strength.
- Change in MSE responds to change in the formation as highlighted by black dotted box in **Figure 6**.

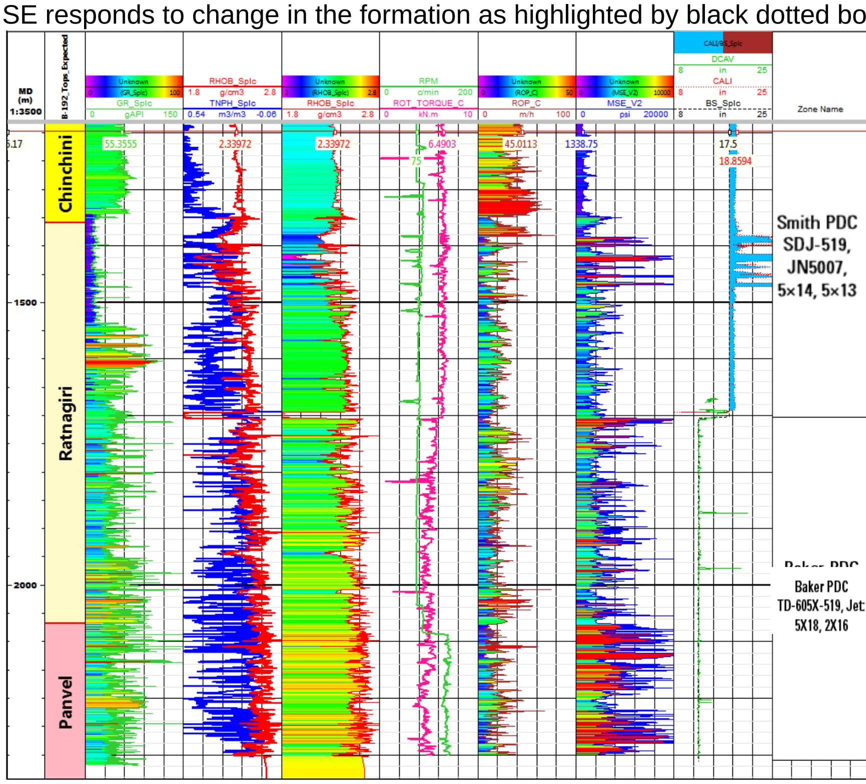


Figure 6: Understanding the Bit Performance with MSE and petrophysical evaluation in Mesozoics Formations for Well-XZ-1

Conclusions and Concerns

- The MSE and rock strength concept describes the amount of energy used for drilling a given volume of rock – the interval of inefficient bit operation can be detected. MSE is the energy used for drilling, minimum MSE values and maximum ROP values can be recommended.
- Mechanical specific energy proves to be useful in many areas of drilling, but cannot be defined as anything more than a tool to aid identification of mechanical drilling inefficiencies. The main advantage of using mechanical specific energy and rock strength together is that they can act as an enabler to interpretation by highlighting inefficiencies more clearly and faster than the interpretation of multiple data channels.
- For mechanical specific energy to be used as a tool within the optimization process, the requirements for modeling, risk registers, lessons learned databases exist and should be used to ensure that the knowledge base for MSE use increases on a well-on-well basis and knowledge is effectively managed. The operator's knowledge of the expected bit life and offset performance is a key factor in deciding to pull the bit based on an observed MSE / UCS trend.
- Two case studies have been discussed in brief in the paper. In the first case study, analysis has assisted in developing a better understanding of drillability of different bit types used (PDC and TCR). It was found that PDC performed better than the TCR bits. It is also observed that difference between MSE and rock strength is inversely proportional to the ROP. In the second case study, it is seen that, MSE can also be used to identify Formation changes.
- One of the primary challenges using this MSE analysis to get downhole bit parameters. Most of the times surface drilling parameters are available for analysis.

References

1. Martin J.S Hayes: "Mechanical Specific Energy and Drilling Efficiency Calculations in Drilling Optimization, Schlumberger.