

Mechanical Specific Energy Analysis of the FORGE Utah Well

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ABSTRACT

One of the key findings of the 2014 Petroleum Practices Technology Transfer Committee report led by National Renewable Energy Laboratory (NREL) was that the geothermal drilling process lacked proper data collection while drilling, data integration, and analysis of such data. The lack of this essential engineering, well planning, and construction tool seemingly adds a significant amount of time to the 12-day additional non-productive time (NPT) at average per well while drilling geothermal wells versus oil and gas wells out of the 42 wells studied of the comparable order of magnitude of construction complexity. Geothermal Resource Group (GRG) has recently been involved in the construction of a well for a unique domestic enhanced geothermal system (EGS) observation drilling project (FORGE Utah) and was able to implement a hydraulic surface torque data collection system on a mechanical rig to analyze the MSE (mechanical specific energy). This paper presents the collection, evaluation, and the post-mortem comparison of the MSE to the drilling history, parameters, and changes in general lithological structures of this well.

1. INTRODUCTION

Geothermal Resource Group (GRG) has been involved in the construction of a well for a unique domestic enhanced geothermal system (EGS) observation drilling project (FORGE Utah) and was able to implement a hydraulic surface torque data collection system on a mechanical rig to analyze the MSE (mechanical specific energy). This paper presents the collection, evaluation, and the post-mortem comparison of the MSE to the drilling history, parameters, and changes in general lithological structures of this well.

Mechanical Specific Energy has been utilized in the oil and gas industry for the past 5 decades in various forms and flavors. Simply stating, Mechanical Specific Energy (MSE) is conservation of energy which states the amount of energy and work done to cut a volume of rock should be equal and conserved throughout a closed system that includes top drive, circulating system etc. In reality however, energy to drill a volume of rock is not conserved due to several factors and therefore does not necessarily translate into the net effective rate of penetration. The use of specific energy to correlate formation characteristics have been explored by several authors as seen in the literature. However, all these studies belonged to the conventional shallower drilling applications. Today with the evolving of technologies and downhole sensors, Mechanical Specific Energy is widely used in the oil and gas to improve performance and provide a real time feedback loop to the driller on the downhole formation transitions. Rate of Penetration and re-engineering of technical limits that are hindrance to performance such as top drive limits, bottom hole design specifications, redesigning of bits to mention a few have been performed based on specific energy measurements at the bit.

The lack of this essential engineering well planning, and construction tool in the geothermal industry, presumably adds a significant amount of time to the 12-day additional non-productive time (NPT) at average per well while drilling geothermal wells versus oil and gas wells, out of the 42 wells studied of the comparable order of magnitude of construction complexity.

2. MECHANICAL SPECIFIC ENERGY

Mechanical Specific Energy has been a widely used tool to reduce total days of spud to rig release as much as 60% and therefore lowering costs of drilling to 30-40%. In this paper, we explore the use of MSE to hard rock – specifically granite application and understand how the real time drill-off tests and qualitative trending tool can be used to reverse engineer formation properties and their variance from actual cores and log data. Data such as Uniaxial and confined compressive strengths, Youngs modulus, Biot's constant and pore and fracture pressures can be back calculated from dynamic MSE values. This is also a common method to reduce costs that is being widely applied in the unconventional industry which don't do much logging and infer the rock characteristics. Published MSE equations from literature have been used to keep the investigation simple and focused on hard rock drilling in a high temperature environment. As this is an experimental well for University of Utah, most data have been analyzed on a reactive way than a proactive way to use it as a tool for improving performance in real time way. With the acquisition and analysis of data, the interpretation of MSE can be a very powerful tool to provide to the driller and at least save 15-20% of drilling days (to be most conservative). This should be recommended to be used as a real time application for the next phase of the Utah Forge drilling and made aware to crew, DOE and its significance to improve geothermal drilling applications. This paper will address the reasons why MSE is crucial for all geothermal drilling applications and how the energy at the bit can be translated to improve ROP and also show what measurements can be inferred in a developed basin without use of highly sophisticated measurements and logging tools such as NMR, LWD, Sonic-scanner and density neutron tools.

There is a real opportunity to improve performance in granitic formations and understand how real time drill-off tests and qualitative trending tools can be useful for improving performance. This paper goes one step further. Ideally, the analyst should be able to use the bit as a laboratory and determine at the least the formation mechanical properties (El-Biblawi et al., 2007; Detournay and Defourny, 1992; Detournay and Chan, 2002; Shewalla and Smith, 2015; ...). It should be possible to reverse engineer formation properties and assess their variance from actual core and log data.

3. FORGE UTAH WELL

With increasing interest in Enhanced Geothermal Systems, EGS, efficient and informative drilling becomes essential. This was an opportunity for back analysis of a drilling operation that has been part of the United States Department of Energy’s FORGE program. The acronym FORGE stands for Frontier Observatory for Research in Geothermal Energy. “The FORGE Utah site is located 350 km south of Salt Lake City and 16 km north northeast of Milford, Utah, in an unpopulated area that is predominantly used for renewable energy, including wind, solar, and geothermal generation. The site lies 5 km west-northwest of the Blundell geothermal power plant, which produces 35 MWe from flash and binary units.” (Simmons et al., 2018).

“Well 58-32 was spudded on July 31, 2017 and was drilled vertically to 7,536 ft (2,298 m) depth in 57 days. The well penetrated layered alluvium deposits down to 3,176 ft (968 m), where it crossed the contact with underlying crystalline basement rocks, which make up the rest of the stratigraphy to the bottom of the hole. Drill cuttings were collected every 10 ft and samples of core were collected from two intervals at 6,800-6,810.25 ft (2,073-2,076 m) and 7,440-7,452.15 ft (2,268-2,272 m). The cores were logged for their physical and lithologic properties, photographed, CT-scanned and plugged for mechanical testing. A complete suite of geophysical logs was run (2,172-7,536 ft), and the hole was then lined with 7-inch casing down to 7,375 ft (2,248 m).” (Simmons et al., 2018)

Diagnostic Fracture Injection Testing (DFIT) was performed in a barefoot section of the hole to determine in situ stresses, permeability and reservoir pressure. Figure 1 shows a cross-section of the FORGE site. Notice the plans for two future wells to be interconnected with hydraulic fractures.

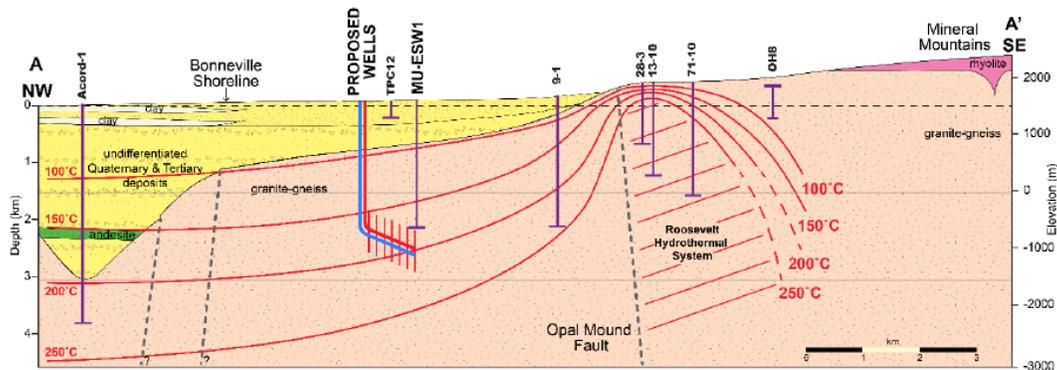


Figure 1: This a NW to SE (A to A’) cross-section showing the top of the crystalline basement rocks in the Milford Basin in the vicinity of the FORGE site. Precambrian gneiss and Tertiary plutonic rocks are undifferentiated. The Roosevelt Hot Springs hydrothermal system lies east of the Opal Mound fault. Isotherms are interpreted from well measurements. The figure shows the proposed FORGE injection and production wells and the vertical 2134 m deep test well (originally MU-ESW1, now referred to as 58-32) drilled (after Moore et al., 2017).

Balamir et al., 2018, describe drilling operations for this well. 20” conductor pipe was cemented with the casing shoe at 83.5 ft. in advance of the arrival of the drilling rig. The rig completed mobilization and rig up on July 30, 2017 and drilling commenced on July 31, 2017. The 17-1/2” hole was drilled to 342 ft. (relative to Kelly Bushing Height (RKB) of 21.5 ft.) and 13 3/8” casing was cemented to 338 ft. on August 2, 2017. Drilling of the 12-1/4” hole commenced the next day and continued to August 6, when the casing point was reached at 2,180 ft. 9-5/8” casing was set and cemented at 2,172 ft MD on August 7. Drilling 8-3/4” hole commenced on August 8, and total depth of 7,536 ft MD was reached on Sept 14, 2017. Two cores (totaling 35 ft in length) were collected; one starting at 6,800 ft. and the second starting at 7,440 ft. A supplementary extensive logging, injection, testing and measurement program has provided an excellent opportunity for evaluating mechanical specific energy principles in a strong, high temperature (297°C), high modulus environment. Figure 2 is the mud log from the well, showing the ROP record in Track 1 (about 10 feet per hour).

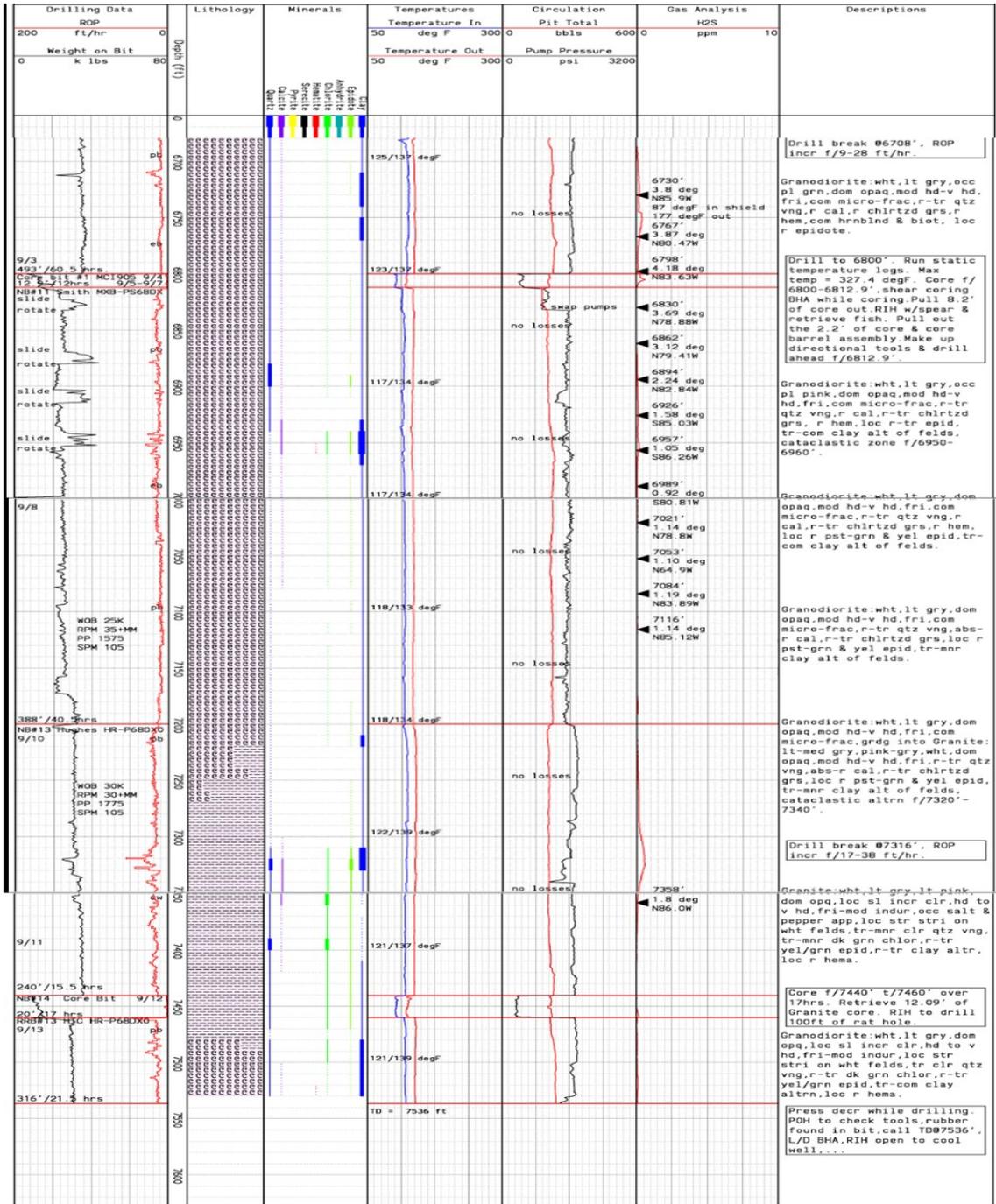


Figure 2: Mud log from Well 58-32. At the extreme left is the rate of penetration, approximately 10 ft/hr.

3.1 Analysis

Standard core analysis was used to determine mechanical properties (Young’s modulus, Poisson’s ratio and Mohr-Coulomb failure parameters. Figure 3 is an example. Standard logging interpretation was used to infer stresses and dynamic mechanical properties. These predictions were calibrated using DFIT and microhydraulic fracturing and laboratory modulus measurements.

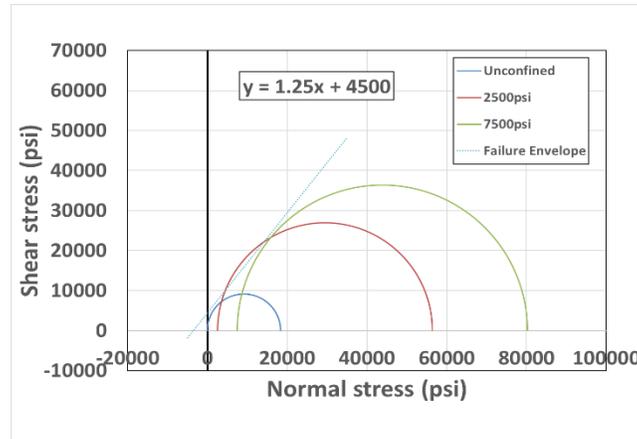


Figure 3: One of eight Mohr-Coulomb failure envelopes for samples plugged from core from Well 58-32. All of the envelopes are characterized by strong, brittle rock.

A post-mortem BHA study and modeling were carried out. Well 58-32 was drilled with 22 BHAs from spud to TD, including two core runs. These evaluations focused on three to four BHAs used near the top of the core runs, one PDC bit that was run, and depths where real time drill off tests were carried out. All of the evaluations were in the 8 3/4-inch hole sections.

The components of the BHA were analyzed using Landmark’s WellPlan® software to evaluate the critical speed, torque and drag to predict the torque of the actual well drilled. This predicted torque was seen to be extremely low in the 8 3/4” hole section. However, in reality the actual torque that was estimated from rotary table pressure was very high. This suggests that severe helical and sinusoidal buckling had occurred. To confirm this, photographs of the bits (Figure 4 is an example) were analyzed on every face, blade and shoulder of the bits following the International Association of Drilling Contractors’ specifications. The results proved excess wear on the face of the blades and cutters (broken teeth, dull gauge) rather than at core of the bit. When severe buckling occurs, there is more torsional vibration in the drill string. This will result in:

1. Higher torque as seen in the results as the buckling tends to amplify the vibrations. When the sinusoidal and helical buckling occurs, the effect is 4x the initial vibrations and as a result 16x less energy translating downhole to the bit.
2. Energy losses through high vibrations
3. Lower Rate of Penetration
4. Damage to the bits on the gauge, shoulders of the blades of PDC bits and broken bits tooth.



Figure 4: Pulled bit, showing excess wear on the face of the blades and cutters (broken teeth, dull gauge) rather than at core of the bit.

3.2 MSE calculations

MSE was first defined by Teale, as the Input Energy divided by the Output ROP. This ratio is likely to be constant for a given rock strength and hold down pressure. This implies that the numerator is the net energy that is input into the rock below the bit – corrected for operational losses associated with torque, drag, vibrations and other losses. Knowing and understanding the MSE will allow real-time decision making to adjust the drilling system for the current rock strength (Balamir et al., 2018). Over the years, this basic relationship has gone thru numerous improvements attempts.

For Well58-32 the formula to calculate MSE is as shown:

$$MSE = \frac{480 \times T \times RPM}{d_{bit}^2 \times ROP} + \frac{4 \times WOB}{\pi d_{bit}^2}$$

where:

MSE.....Mechanical Specific energy (psi)

T..... Torque (ft-lbf)

RPM.....Revolutions per minute (1/minute)

d_{bit}..... Bit diameter

ROP..... Rate of penetration (ft/hr)

WOB..... Weight on bit (lbf)

Following Dupriest and Koederitz, 2005, efficiency factors (0.35 is common) may be applied to the calculated specific energy. Vibrations, torque and drag corrections and modifications for mud motors are usually applied to determine the energy that is reaching the rock. It is also well known that the ability to break rock beneath a bit is a function of the so-called “chip hold down” pressure (Balamir et al). It follows that the MSE should incorporate this in terms of a difference between the bottomhole pressure and the formation pressure ahead of the bit (wellbore pressure minus pore pressure). Majidi et al., 2016, provided a method (DEMSE – Drilling Efficiency and Mechanical Specific Energy) where drillability and MSE were used to estimate the pore pressure. These authors indicated that the energy expended at the bit to remove a unit volume of rock is a function of pressure difference between the mud weight and the formation pressure ahead of the bit – another MSE application.

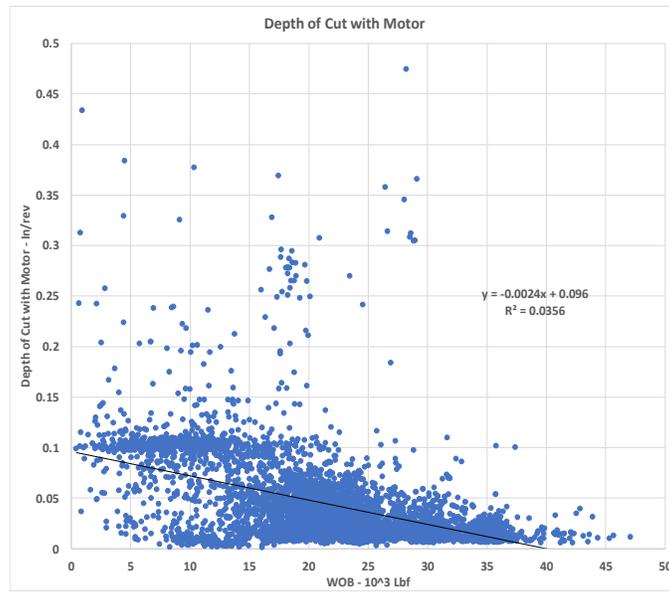


Figure 5: Cross plot of WOB vs depth of cut (in/rev) – depth of indentation by shearing and grinding action of the bit. Motor depth of cut considers cut with a motor with hydraulics action

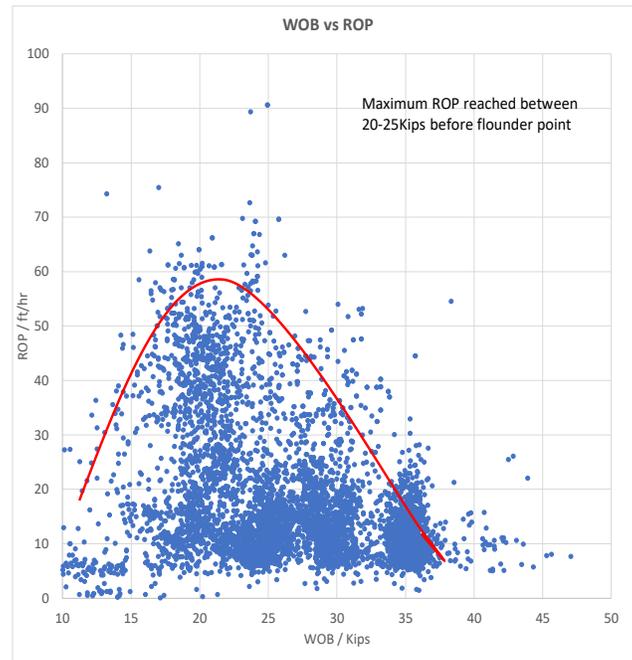


Figure 6: This demonstrates Dupriest’s (2005) flounder point curve with an ROP limitation. Weights greater than 25,000 lbf correlate with a diminishing ROP, due to bit whirl and models used in understanding buckling limits. In the future, BHA design has to be investigated to reassess drilling any well.

4 Conclusions

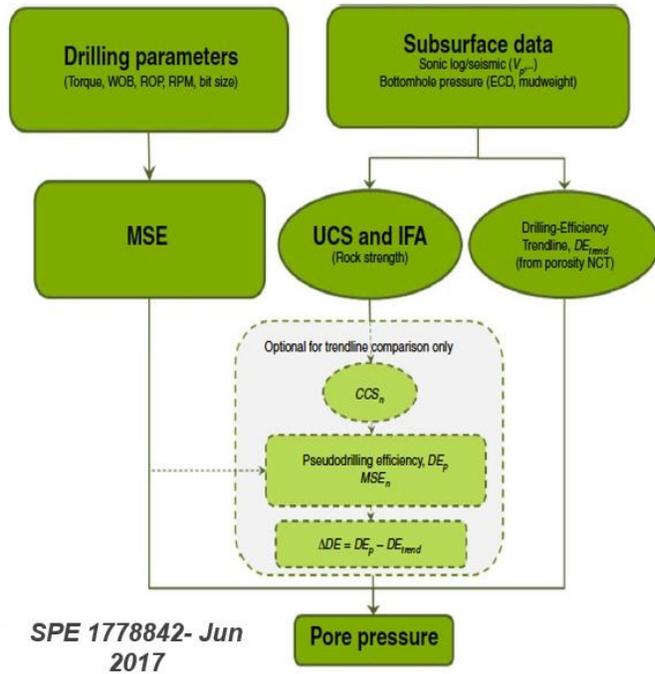
The post-mortem comparison of the MSE recollected at Well 58-32 provides helpful data interpretation to improve future drilling for the FORGE project and the Geothermal Industry as a whole:

The general observation was that bit whirl was the main cause of bit failures and multiple trips rather than buckling. To keep bit whirl in check, next wells have to be drilled with a higher weight on bit than has been drilled in the current well. Some other observations are noted below to improve drilling performance in the next sets of geothermal wells.

- When using a downhole motor (mud motor) it is possible to use the differential pressure across the motor and the pump rate to calculate the torque right at the bit and the actual downhole bit speed.
 - This is also called the Bit MSE and it's become the preferred practice over the last 3-4 years.
 - It is planned to compare this with the surface MSE data in future wells, to validate the difference.
- Plan to use higher weight on bit with a packed BHA design will help to keep the hole straight and prevent bit whirl dysfunctions that will prevent pulling out the bit green.
 - A modern PDC diamond does not wear in the traditional sense.
 - Any wear you see in bit picture 4 is due to whirl, stick slip, or interfacial severity, this particular bit was damaged by whirl.
 - Running a higher WOB it would have caused less wear in the bit, because it would have less whirl.
- PDCs bit have a higher friction coefficient and only drill slower than an insert bit if you run less WOB (as proven in this well). Lower weight on bit was run due to the drift caused in the upper section of the well.
- The wear equations found in literature for insert bits are usually bogus. The wear rate is highly dependent on whirl that is not reflected in lab work. The insert bit picture shows broken inserts on the shoulder which are indicative of lateral impact from bit whirl. The other teeth are worn, and the bit was ready to be pulled, but if the whirl had been minimized the bit would have gone much further before it arrived at this level of damage and wear. Like the PDC, this bit needs more WOB.
- Critical speeds cannot be calculated accurately because true numbers for the BHA components are rarely known. It's much better to just run RPM step tests as soon as you drill out of casing and watch MSE to see when whirl is higher or lower. At critical speeds the higher BHA whirl will cause more stabilizer drag and the MSE will rise because of the higher torque without a proportionate increase in ROP (meaning the torque is not in the bit).
- Torsional vibration does not cause stab wear because it does not increase the force acting normal to the face of the stab, whirl does. If there's accelerated stab wear it's due to whirl.
- The depth of cut (DOC) is a function of WOB and does not change with RPM, so DOC does not change for a motor. But the higher RPM of a motor should always result in more ROP for the same DOC. ROP is linear with both WOB (indentation) and RPM (sliding distance per minute at the indentation depth). If the motor did not drill fastest it was because the driller chose to run less WOB on it, or an insert was used instead of a PDC (less DOC for given WOB).
- The results of the DOC plots shown in figures above are distorted by decisions the driller is making. They are generally keeping their WOB below 20-35k lbs. The only time they go above this is when the ROP falls (harder rock, more whirl, or dull bit). The lower DOC is not a product of the higher WOB, the higher WOB is a product of them seeing a lower DOC (ROP) and responding with higher WOB.

Mechanical Specific Energy (MSE) is the energy required to destroy a given volume of rock. MSE surveillance is used as a real-time diagnostic tool to identify current ROP limiters and tell you if the bit is becoming more or less efficient when you make parameter changes. Goal is to mitigate these ROP limiters through changes in operational parameters and/or engineering design.

$$MSE_{psi} = \frac{\text{Input Energy}}{\text{Resulting ROP}}$$



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When to Perform MSE Step Test

- Beginning of each work shift
- Formation change
- Bit or BHA change
- Predetermined intervals agreed upon in drilling procedure
- Slide drilling: increase **WOB** to determine the most efficient drilling without compromising tool-face control
- Additional tests are recommended every 5-6 hours to validate/confirm optimal parameter selection

Improving Our Performance



- If you change WOB or RPM and:
1. MSE goes up → Quit doing that
 2. MSE goes down → Keep doing that
 3. MSE stays the same → Raise WOB/RPM

- All limiters lie on a single line, which allows us to prioritize them
- There can be only one, at a given moment in time

REFERENCES

Islam, N., Vijapurapu, R., Jones, M., McLennan, J., Moore, J., Rickard, W. and Balamir, O., Vagnetti, R.: Application of Mechanical Specific Energy and At-the-Bit Measurements for Geothermal Drilling Applications in Hot, High Strength, High Modulus Reservoirs, ARMA

Dupriest, F.E., and Koederitz, W.L., "Maximizing Drill Rates with Real-Time Surveillance of Mechanical Specific Energy", IADC/SPE paper No. 92194 presented at SPE/IADC Drilling Conference, Amsterdam, The Netherlands, 23-25 February, 2005

Rashidi, B., Hareland, G., and Nygaard, R. 2008. Real Time Drill Bit Wear Prediction by Combining Rock Energy and Drilling Strength Concepts, IADC/ SPE 117109, Abu Dhabi, UAE, November.

Teale, R.: "The Concept of Specific Energy in Rock Drilling", Intl. J. Rock Mech. Mining Sci. (1965) 2, 57-73