An Experimental Investigation of Drilling Performance Improvement Using Reaming While Drilling

Abbas Roohi¹, Rahman Ashena², Gerhard Thonhauser¹, Thomas Finkbeiner³, Laurent Gerbaud⁴, Vamegh Rasouli⁵

¹ Montanuniversitaet Leoben, Austria
² Asia Pacific University of Technology and Innovation (APU), Malaysia
³ King Abdullah University of Science and Technology (KAUST), Saudi Arabia
⁴ Armines–MINES ParisTech, France
⁵ University of North Dakota, USA

Abstract

This work investigates the drilling performance by reaming while drilling (RWD) using a dual-body bit and compared it with conventional drilling by a standard drilling bit. The dual-body bit consisted of a 2.45-in pilot bit located at a short distance ahead of a 2.47×3.97-in reamer.

Conducting a series of drilling experiments at a simulation drilling rig with full monitoring sensors, we further studied the drilling performance as a function of the distance between the pilot bit and the reamer. This distance is a greatly important parameter affecting mud diffusion and the resultant change in pore pressure and stress. A method was devised to eliminate the drill-string vibration and its effect on the drilling performance and the energy consumed. The mechanical specific energy (MSE) calculated for each case was considered as a drilling performance indicator. Using two laboratory experiments as well as analytical thermo-poroelastic calculations of the Mechanical Specific Energy (MSE), the MSE changes were monitored and recorded. Comparison of this drilling performance indicator was used in both the RWD and the conventional drilling assembly to analyse the effect of RWD.

Based on the results, with increasing the distance between the pilot bit and reamer, there is an increase in improvement of drilling performance in terms of MSE reduction. The best drilling performance indicator (MSE reduction of 84%) was observed with the greatest distance between the pilot bit and the reamer of 43.3 cm. The best drilling performance indicator (MSE reduction of 84%) was observed with the distance between the pilot bit and the reamer of 43.3 cm. This is considered a novel finding in reaming while drilling.
1. Introduction

Drilling is a costly activity with rig costs reaching in excess of 1 million USD/ day [1]. The expenses of cuttings rocks are greater in hard formations which are usually encountered in high pressure high temperature (HPHT) where strength of rocks is generally greater than shallower formations, or geothermal wells drilling where rocks are igneous and harder to drill than sedimentary rocks which are usually encountered in oil and gas operations. Therefore, a small saving will be a significant amount to contribute to drilling industry’s expenses reduction.

Improving the drilling performance has a great contribution to the overall economy of a development project and therefore has been the subject of many studies [2-9]. Reaming While Drilling (RWD) is one of the techniques contributing to the drilling efficiency [10-11]. However, this technology has very limited track records with very rare onshore and a few offshore cases in the hundreds of thousands of wells drilled in North America. Therefore, there has been little research in the area. There are several RWD techniques, one of which is the dual-body bits as is discussed in this work. The RWD topic has been also considered for slim-hole wireline continuous core drilling [12-14]. Dual-body bits have several provided several advantages in improving the drilling performance including:

- Setting larger casing strings deeper into the holes across the sections with potential wellbore instability, high-pressure zones and lost circulation intervals, which will eliminate numerous trips, hence reduces the exposure times of the open-hole section of the wellbore with the drilling fluid. This will potentially mitigate the chemical related instabilities due to the fluid-rock interaction.
- Greater annulus clearance between the casing and the wellbore is provided by the reamer, which can render an improved cement job.
- Providing a sufficiently large borehole and more complex completion string access to reservoir has several advantages for exploration and production wells [15].

Despite the advantages, the deployment of two cutting tools (i.e., the pilot bit and reamer) in the bottomhole assembly (BHA) leads to additional drill-string vibrations because the weight and torque will be distributed between the pilot and reamer [10-16]. Therefore, hole enlargement generally suffers from downhole tool failures, shorter BHA life-time, lower drilling performance, poor borehole quality, and compromised directional efficiency [11]. These drilling problems are rather detrimental and have negative effects on drilling budgets, in particular in deep-water drilling [17].
In order to understand the performance improvements that can be achieved using RWD over conventional full-hole bits, it is important to first look at the effects of the drill bit penetration on the formation and its in-situ stresses, and the pore pressure diffusion into the rock surrounding the bit. Drilling into a formation causes alteration of the stress state [18] and the stress concentration affects the near wellbore area as well as the bottom of the hole ahead of the bit. The resulting hoop stresses are characterized by a highly compressive and a tensile region around the wellbore and amplifies the ambient in-situ differential stress by a factor of four [19]. In addition, temperature differences between the drill mud and the rock causes cooling particularly in wells deeper than 2.5 km [19] with minor wellbore strengthening. The two effects of pore pressure and temperature diffusion result in weakening of the host rock during the drilling process. However, as stated by [20], most conventional drill bits gain little advantage from this weakening effect. In contrast, RWD tools make effective use of this stress alteration due to their configuration. The pilot hole section of the RWD is drilled as a conventional hole; however, due to its smaller diameter bit, less rock volume is required to be removed. It thus leads to an improvement in the rate of penetration (ROP) in comparison to a larger diameter bit. In the following sections, we quantify and analyse this improvement and the dependent parameters. When the reamer section follows to enlarge the hole to its full diameter, it does so through a stress-altered and weakened rock zone with the consequence that it requires less power to cut the remaining rock. This process is manifested by a notably lower MSE values.

An efficient method of investigation of rock weakening around the wellbore is based on a thermo-poro-elastic modelling (see [21-23] for drilling and [24-25] for coring). In this approach, the so-called Analytical Mechanical Specific Energy (AMSE) is estimated for a certain radius of wellbore (Figure 1) by averaging the Apparent Rock Strength (ARS) at the in-situ stress conditions. The mathematical equations are provided in section 3 “Test Procedure”.

Utilizing this model, Figure 2 [22] presents isochrones of pore pressure and AMSE around the borehole for a permeable rock sample. In this figure, as the boundary condition, the pore pressure is considered equal to the mud pressure at the borehole wall. Because of the overbalanced drilling condition, there is a considerable pore pressure drop near the borehole at early times. As time passes by, with mud infiltration through the permeable rock, the pore pressure shows to increase.

In order to compare the ARS at the wellbore wall (after the pilot bit has drilled) with the intact rock lying underneath the pilot bit, the method presented by [26] was followed in this work. The minimum and maximum ARS values for permeable and impermeable formations
respectively are plotted on the same figure (top blue and bottom red horizontal bold lines in Figure 2b). The findings from this figure are in line with qualitative discussions of [20] which implied the advantage of dual-body bits in relieving the stress state of the surrounding rock.

The zone of weakening (i.e., with reduced rock strength) starts at the wellbore wall and then progresses with time further into the ambient, undisturbed zone of the formation rock. In other words, in early times after drilling the pilot hole when the zone of apparent weakening has not yet progressed very far away from the wellbore wall, the reamer size should only be marginally larger than the pilot bit. However, if the hole enlargement process with the reamer occurs after a longer time period following the pilot bit, then the weakening zone is predicted to have extended further into the ambient rock formation in response to hydraulic and thermal diffusivity. This allows for a larger reamer size taking advantage of the further enlarged zone around the well with reduced rock strength. In addition, when the ROP is lower, the benefit from wellbore weakening would be greater.

Roohi et al, (2016-a and b) concluded that using the RWD method in a medium-permeable formation with permeability of 1 mD ([21]) in water-based muds, resulted in greater drilling efficiency, when compared with the conventional approach of using a full-hole drill bit size that drilled the entire hole size at once. The discussions in [22-23] analytically demonstrated the benefit of using multi-diameter RWD system to create weakening of the zone prior to the involvement of reamer in drilling, and the optimum reamer to bit size ratio as well as the distance between them. In the mentioned work, a medium-permeable formation (with permeability of 1 mD) was considered to be drilled using an RWD system composed of a reamer installed 15 m above the pilot bit, with 20% larger in size than the pilot bit, and a typical rate of penetration (ROP) of 30m/hr was assumed. In this case, it was inferred that the resultant MSE would be 17.5% lower than when a full-hole bit (with the same bit specifications) was used to do the drilling job. The MSE reduction would be greater with a lower ROP due to increased wellbore weakening.

To validate the mentioned analytical findings by [23] about the effect of using a reaming while drilling system on wellbore weakening, this work focuses on an experimental investigation and validation. This was carried out by using a developed RWD pilot-reamer configuration and an engineered procedure of drilling rock samples in a fully monitored drilling test facility setup. Therefore, MSE can be compared in the two drilling cases with a full-hole drilling bit and an RWD system (see Figure 3).
2. Materials and Experimental Setup

As the required materials for the experimental work, some sandstone rock samples called “Gres Des Vosges” were prepared from the test center at Armines-Mines ParisTech. The rock mechanical properties of the samples are given in Table 1. Next, a water-based mud was made up of water and bentonite with the weight of 8.68 ppg; the required mud pressure to simulate the drilling conditions was provided hydraulically.

In this work, an RWD system was designed and developed using a crossover sub (XOS), which allowed connecting the 2.45-in PDC pilot bit and the 2.47×3.97-in (2.47-in ID / 3.97-in OD) PDC reamer with an adjusted distance between them as needed (see figure 4 and 5). Since the DTF’s connection to a bit was dressed with the 2 3/8-in Regular Box thread, the XOS was designed accordingly with a 2 3/8-in Regular Pin thread. Therefore, the pilot bit and the reamer could be connected concurrently as depicted in Figure 4. In addition, a 10-cm extension sub was constructed to provide some distance between the pilot bit and the reamer (see figure 5). The mentioned distance was considered low enough so that the drill-string vibrations can be almost eliminated and ignored.

The test facility to conduct the drilling tests was the Drilling Test Facility (DTF) of ARMINES-MINES ParisTech. Figure 6-a depicts the drilling test facility in a schematic view with components shown; figure 6-b shows a photo of the facility. The test facility allowed drilling roller-cone or fixed cutter bits of up to 8 ½-in size and also allowed the simulation of deep-hole drilling conditions. The drilling tests can be performed under constant WOB or constant ROP. In this work, the tests were carried out under constant ROP. The rock can be held in a pressure vessel, and upon the conclusion of the test, the bit and the bottomhole pattern can be examined visually. The drilling test facility allowed simulation of the complex downhole stress conditions of a cylindrical rock sample exposed to drilling. In particular, the following four stresses and loads can be controlled using this system: (a) the maximum compressive horizontal stress along the x-direction; (b) the vertical principal lithostatic stress (overburden pressure) directed parallel to the wellbore axis in the z-direction; (c) the drill-string weight applied vertically and uniformly at the bottom of the drill bit; and (d) the wellbore mud or fluid pressure acting perpendicularly to the wellbore wall [27].

In the test facility, two options were available in order to test the impact of temperature on the rock strength. The first option was to circulate high temperature mud prior to testing in order to heat up the rock sample. The second one was to heat up rock sample in an oven. We pursued
the latter option as it was less time-consuming compared to the first one. The rock sample was left in the oven over night to heat up. The sample was heated to an ambient temperature of 80 °C while the mud temperature was kept at 20 °C in order to create a temperature differential of 60 °C. Such a temperature difference is typically achieved in 3 km deep wells located in areas of normal heat flow characterized by a geothermal gradient of 20 °C/km.

3. Test Procedure

Two similar experiments were carried out in this work. During the operation, all the dynamic drilling parameters were measured real-time with the frequency of one HZ (one measurement per second).

3.1. First Experiment:

The procedure of the first experiment is described stepwise as follows:

1. Drilling is carried out using the RWD system to 10 cm deep in the rock. In this part, only the pilot hole is engaged in drilling because the reamer, which was 10 cm behind the pilot bit, has not yet reached the rock. As this is the first rock thickness to be drilled, it is called as the first zone in this work. It should be noted that the properties of the rock zones remained almost the same and the term “zone” or “phase” indicates the interval of rock drilled with constant drilling conditions.

2. Drilling is continued until the reamer starts tagging the rock and getting engaged into drilling together with the pilot bit. Drilling this rock interval with combined pilot bit and reamer is called the second zone.

3. Drilling is stopped for 60 seconds (one minute), during which, only WOB is reduced to zero and other parameters are kept identical to those of the drilling conditions.

Note-1: A drilling stoppage or pause period, depending on its period, was designed by the authors to allow further time for mud and temperature difference diffusion into the surrounding wellbore rock, for purpose of wellbore weakening. The pause was indeed applied as an analogy to simulate drilling with distance between the reamer and the pilot bit greater than the real 10-cm. The main objective of the authors to design such a testing plan was to eliminate the vibration impact on drilling efficiency and consumed energy.

Note-2) As the rock samples were medium permeability (1 mD) sandstones, the process of mud diffusion into the formation was quick. Therefore, the pause periods applied in this experimental work ranged from 1 to 20 minutes.

4. Drilling is resumed and the third rock zone is cut using the pilot bit and the reamer.
5. Drilling is again paused for 180 seconds / three minutes in order to increase the effect of wellbore weakening. As was the case with the previous pause, the WOB was removed in this period, whereas mud circulation and rotary speed are still on.

6. Drilling is resumed to drill the fourth rock zone. With this procedure, the pilot bit will be involved in drilling four rock zones/sections and the reamer is involved in drilling three zones. This will be covered in “Results and Conclusions” section.

7. The MSE values are calculated versus time for each of the rock zones drilled and compared.

Note: MSE is defined as the required energy for cutting/destroying a unit volume of rock. The MSE is related to the apparent rock strength, ARS:

\[
AMSE_i = \frac{\sum (ARS_{area,i} \times A_i)}{\sum A_i}
\]  

(1)

where:

\(AMSE_i\): Analytical Mechanical Specific Energy [psi]

\(ARS_{area,i}\): Apparent Rock Strength [psi] or the rock Uniaxial Compressive Strength (UCS) (Caicedo, et al., 2005)

\(A_i\): Area of the rock segments below the pilot bit or the reamer [in²]

Practically, MSE is found using the following relation:

\[
MSE = \frac{WOB}{A} + \frac{120 \pi \times TOB \times RPM}{A \times ROP}
\]  

(2)

where:

MSE = Mechanical Specific Energy [psi]

WOB = Weight on the Bit (lb)

RPM = Rotary Speed or Revolutions Per Minute [1/min]

A = Bit Area [in²]

TOB = Torque on the Bit [ft.lb]

ROP = Rate of Penetration [ft/hr]

3.2. Second Experiment:
The procedure of the second experiment is similar to the first experiment, except that two longer pause periods of 5 and 20 min were allocated. Longer pause time periods were applied to further investigate the effect of longer pilot-reamer distance contributing to further mud diffusion or filtration into the rock and the resultant wellbore weakening.

4. Results and Discussion

Table 2 shows general drilling parameters during the experiments, consisting of the ROP, maximum allowable WOB, RPM, pore pressure, confining mud pressure, overburden pressure, mud type, mud temperature, and rock temperature. The ROP was auto set at 4 m/hr and WOB was automatically adjusted to reach the target ROP. The RPM was maintained at 85 during the test.

As explained in section 3 “Test Procedure”, some pause periods were applied intermittently between drilling phases in order to investigate effects of different durations of mud filtration or diffusion on weakening of the wellbore. The pause periods are translated as different distances between the pilot bit and the reamer. For example, with the average ROP of 4 m/hr, a 1-minute pause period is equivalent to an additional 6.6 cm distance between the pilot bit and the reamer (that is, $4 \frac{m}{hr} \times \frac{hr}{60min} \times \frac{100cm}{m} \times 1min = 6.6cm$). Therefore, including the original 10 cm distance between the pilot hole and the reamer, the equivalent distance between the two would be the total of 16.6 cm. The total equivalent distance between the pilot bit and reamer for 3-minute and 5-minute drilling pauses will be respectively 30 cm and 43.3 cm (as given in Table 3).

Figure 7 shows drilling parameters and in-situ stress conditions for the first experiment. Figure 7-A shows RPM, bit depth, ROP, WOB and TOB versus time. Figure 7-B shows the calculated MSE, pore pressure, mud pressure, confining and overburden pressures as well as the Unconfined Compressive Strength (UCS) and Confined Compressive Strength (CCS) versus time. In the first experiment, there are four phases of drilling during which four zones of rocks were drilled, as shown in Figure 7-A. These zones were discriminated as the drilling conditions differed and thus their MSE values were different, while the rock properties were almost the same. The first zone shows the drilling parameters which were obtained as the result of pilot-hole drilling with an average MSE of approximately 95 k-psi (see Table 3). Appendix shows all the MSE calculations listed in Table-3. In the second zone, the reamer reached and tagged the rock sample to begin drilling simultaneously with the pilot bit. During this time, the average MSE decreased to 85 k-psi, which indicates 11% reduction from the original MSE based on
the same table. This meant that the required power to destroy one unit of rock reduced by approximately 10%, mainly due to rock weakening and stress alteration resulting from the reamer action (to drill the wall around the already existing pilot-hole drilled in the first zone). After drilling was paused for one minute (by removing the WOB while keeping fluid circulation and rotary speed), drilling the next zone was carried out with a further drop of the specific energy to 80 k-psi (which indicates 16% reduction from the original MSE according to the same table). This is attributed to mud filtration or diffusion into the rock causing stress alteration and rock weakening. In order to further evaluate and quantify the effect of the distance between the pilot and the reamer, translated to formation exposure time to the mud system pressure, drilling was stopped for 3 minutes before drilling the next zone. In the 4th zone, due to longer drilling pause simulating longer pilot bit and reamer distance, greater mud diffusion occurred than that of zone-3. Therefore, the pore pressure within the rock increased and this reduced the apparent or effective rock strength to be overcome. Therefore, we see greater drilling performance or efficiency in zone-4. Figure 4 shows that, in zone-4, with lower WOB and TOB, it was possible to obtain significantly higher ROPs than that of zone-3. This practically proves the advantage of the RWD system or using the reamer above the pilot bit in reducing the required MSE. In this zone, the required energy to destroy one unit of the fourth zone rock decreased markedly to as low as 20 k-psi. This indicates 79% reduction from the original MSE based on the same table.

The results of the second drilling test are shown in Figure 8. In this test, longer pause periods of 5 and 20 min were applied. During drilling the first and the second zones, almost the same observations of decrease in MSE as in the first test were made. Drilling with the pilot and the reamer combination was continued to the third zone after 5 minutes pause while mud circulation and rotation were still on. In this zone, the average MSE reduced to 15 k-psi, which indicates 84% reduction from the original MSE based on Table 3. Finally, a 20-min pause period was applied before the last zone was drilled. For drilling this zone of the second test (Figure 8), the operator was rotating off-bottom before reaching the bottom to tag the rock. Due to the vibration of the string during off-bottom rotation, the rock was collapsed, which was not noticed. Because of the wellbore collapse, it was not possible to get enough ROP (low drilling progress). Therefore, the operator increased the WOB to obtain enough ROP. However, this increase in WOB caused total breakdown of the rock and an abrupt drop of the ROP after which the operator proceeded to stopping rotation and putting weight. As off-bottom rotation was a manual mistake causing wellbore collapse, the results are not representative and not reliable.
but due to some manual mistakes and change in operational parameters, the results were disturbed and are not reliable.

Based on the summary results of the experimental works shown in Table 3, with increasing the distance between the pilot bit and reamer, there is an increase in improvement of drilling performance in terms of MSE reduction. The greatest drilling performance in terms of the lowest MSE is observed with the distance of 43.3 cm between the pilot bit and the reamer. It is noted that the drill-string vibration was eliminated in this work by applying an intelligent method of pausing. However, in practice, though the drilling performance is improved because of larger distance between the pilot hole and reamer, the drill-string dynamic challenge will increase due to an increased vibration. Therefore, an optimum distance should be found in real field applications.

5. Conclusions and Future Work

This work focused on investigating the effect of the RWD method on wellbore weakening and drilling efficiency. To achieve that, a reaming while drilling (RWD) system with a 2.45-in PDC pilot bit and 2.47×3.97-in PDC reamer was designed and developed and the experimental tests were made on a medium permeability (1 mD) sandstone.

The following conclusions are made from the results of this experimental study:

1. To investigate the effect of different distance between the pilot bit and reamer, a method was applied to allocate pause periods between drilling phases. This method eliminated the effect of drill-string vibrations on the mechanical specific energy (MSE) evaluations.

2. The use of an RWD system consisting of pilot hole and reamer configuration provided lower mechanical specific energy (MSE) and higher drilling efficiency, compared to the standard drilling operation with an equivalent full-hole bit size. Therefore, it validated the previous analytical modelling results.

3. In overbalanced drilling, the greater the distance between the pilot bit and the reamer, the less the MSE. This is because with greater distance between the pilot hole and the reamer, greater hydraulic mud filtrate diffusion would take place to cause further weakening of wellbore rock. Therefore, reaming the rock around the pilot hole was accomplished more efficiently with less required energy per unit rock volume.

4. With the equivalent distance of 43.3 cm between the pilot bit and the reamer, 84% of the MSE was saved, which is considered an enormous contribution to the drilling efficiency.
5. This work concentrated on the MSE reduction effect of using reamers in a macroscopic scale. Therefore, the limitations of the work are drill-string vibration, micro-fractures, and possible cracks in the rock surrounding to the pilot hole.

6. As a future work, the ratio of reamer radius to the drill/pilot bit radius is an important parameter to be investigated experimentally. This would require using several pilot bits and reamers setups. In addition, investigation of the effect of different temperature differences between the mud and rock is also recommended. The experiments were performed on sandstone rock samples, it is recommended to apply the same experiments on other rock lithologies including igneous rocks (commonly encountered in geothermal drilling) to check the possibility of expansion of results to other rocks.

7. For further validation, the increased drilling efficiency by using reamer with the pilot bit is expected to be observed in field practice.

Acknowledgment

The authors would like to acknowledge Mr Manfred Franzl of Thonhauser Data Engineering Equipment & Manufacturing (TDE E&M), Austria for construction of the crossover sub required for development of the reaming while drilling (RWD) system.

Conflict of Interests Declaration

There is no conflict of interests in this work.

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Cross-sectional area of bit or the borehole area (in²)</td>
</tr>
<tr>
<td>AMSE</td>
<td>Analytical Mechanical Specific Energy (psi)</td>
</tr>
<tr>
<td>ARS</td>
<td>Apparent Rock Strength (psi)</td>
</tr>
<tr>
<td>BHA</td>
<td>Bottom Hole Assembly</td>
</tr>
<tr>
<td>CCS</td>
<td>Confined Compressive Strength (psi)</td>
</tr>
<tr>
<td>DTF</td>
<td>Drilling Test Facility</td>
</tr>
<tr>
<td>ID</td>
<td>Inside diameter (in)</td>
</tr>
<tr>
<td>MSE</td>
<td>Mechanical Specific Energy (psi)</td>
</tr>
<tr>
<td>OBP</td>
<td>Overburden pressure (psi)</td>
</tr>
</tbody>
</table>
OD: Outside diameter (in)

P<sub>p</sub>: Pore Pressure (psi)

ROP: Rate of Penetration (m/hr or ft/hr)

RPM: Revolutions Per Minute

RWD: Reaming While Drilling

TOB: Rotational torque (ft-lbf)

UCS: Unconfined Compressive Strength (Psi)

V<sub>p</sub>: P wave velocity [m/s]

WBM: Water-Based Mud

WOB: Weight On iBit, pilot bit or combination of pilot bit and reamer (lbf)

XOS: Cross Over Sub

References


SPE Western Regional Meeting, Anchorage, Alaska, May 1999. doi: https://doi.org/10.2118/54595-MS.


Appendix: MSE Calculations for Table-3

Test 1 (Zone-1):

\[ MSE = \frac{2910 \text{ lb}}{2.47^2 \pi 4 \text{ in}^2} + \frac{120\pi \times 185 \text{ ft. lb} \times 88 1/\text{min}}{2.47^2 \pi 4 \text{ in}^2 \times 4.13 \frac{\text{m}}{\text{hr}} \times \frac{3.281 \text{ ft}}{1 \text{ m}}} = 95 k – lb \]

Test 1 (Zone-2):

\[ MSE = \frac{1390 \text{ lb}}{3.97^2 \pi 4 \text{ in}^2} + \frac{120\pi \times 221 \text{ ft. lb} \times 89 1/\text{min}}{3.97^2 \pi 4 \text{ in}^2 \times 2.15 \frac{\text{m}}{\text{hr}} \times \frac{3.281 \text{ ft}}{1 \text{ m}}} = 85 k – lb \]

Test 1 (Zone-3):

\[ MSE = \frac{2650 \text{ lb}}{3.97^2 \pi 4 \text{ in}^2} + \frac{120\pi \times 373 \text{ ft. lb} \times 88 1/\text{min}}{3.97^2 \pi 4 \text{ in}^2 \times 3.6 \frac{\text{m}}{\text{hr}} \times \frac{3.281 \text{ ft}}{1 \text{ m}}} = 85 k – lb \]

Test 1 (Zone-4):

\[ MSE = \frac{220 \text{ lb}}{3.97^2 \pi 4 \text{ in}^2} + \frac{120\pi \times 114 \text{ ft. lb} \times 87 1/\text{min}}{3.97^2 \pi 4 \text{ in}^2 \times 4.6 \frac{\text{m}}{\text{hr}} \times \frac{3.281 \text{ ft}}{1 \text{ m}}} = 20 k – lb \]
Test 2 (Zone-3):

\[
MSE = \frac{460 \text{ lb}}{3.97^2 \pi \frac{in^2}{4}} + \frac{120 \pi \times 75 \text{ ft lb} \times 87 \frac{1}{min}}{3.97^2 \pi \frac{in^2}{4} \times 4.05 \frac{m}{hr} \times 3.281 \frac{ft}{1m}} = 20 \text{ k lb}
\]
Figure 1: A small segment of rock around the wellbore (Roohi et al., 2016-b) for estimation of Apparent Mechanical Specific Energy (AMSE). Rim Radius is the radius of the reamer, Pilot radius is the radius of the pilot bit, and of an element with its coordinates shown.

Figure 2: a) the thermo-poro-elastic induced transient pore pressure distribution for permeable formations, and b) the AMSE profile for drilling of the formations (Roohi et al. 2016-a).
Figure 3: Set-up of the experimental test scenario: a) drilling the full-hole using the 3.97-in bit size, b) drilling the 2.45-in pilot hole as the initial drilling stage by the reaming while drilling (RWD) system, followed by enlarging the pilot hole using the 3.97-in reamer as the latter drilling stage.

Figure 4: The schematics of a) the full-hole 3.97-in bit (with the pilot bit and the reamer being integrated), b) RWD pilot bit and reamer arrangements developed in this work. The gray-colored object is the cross-over (XOS) sub. The light blue object is the extension sub providing a 10-cm distance between the pilot bit and the reamer.
Figure 5: the reaming while drilling (RWD) system in two a) cross-sectional and b) the pilot-reamer face views.

Figure 6: a) schematic and b) a photo of the Drilling Test Facility (DTF) at ARMINES - MINES ParisTech.
Figure 7: The first drilling experiment with pilot bit to reamer distance of 10 cm, zero pore pressure 80 °C rock temperature and 20 °C mud temperature. The results showed that MSE decreased after the reamer tagged the rock and was involved in drilling (during which the pilot bit was drilling the second zone), indicating higher drilling efficiency. The pore pressure increased after 280 seconds due to mud invasion. The different rock zones are specified by different colors.
Figure 8: The second drilling experiment with pilot bit to reamer distance of 10 cm, zero pore pressure, 80 °C rock temperature and 20 °C mud temperature. The results showed that the MSE decreased after the reamer tagged the rock and was involved in drilling (during which the pilot bit was drilling the second zone), indicating higher drilling efficiency; the MSE showed a further decrease during drilling the third zone compared with that of the previous experiment. The peak in MSE was observed after about 1,780 seconds, which was due to rock sample breaking into several pieces. The different zones are specified by different colors.

<table>
<thead>
<tr>
<th>Table 1: Rock mechanical Properties of the ARMINES-MINES ParisTech’s sandstone sample called “Gres Des Vosges”</th>
</tr>
</thead>
<tbody>
<tr>
<td>Confining Compressive Strength (CCS)</td>
</tr>
<tr>
<td>Confining pressure [Psi]</td>
</tr>
<tr>
<td>-------------------------</td>
</tr>
<tr>
<td>0</td>
</tr>
<tr>
<td>1,428</td>
</tr>
<tr>
<td>2,856</td>
</tr>
</tbody>
</table>
Other Parameters

<table>
<thead>
<tr>
<th>Rock dimensions:</th>
<th>50×50×50 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porosity:</td>
<td>24.2%</td>
</tr>
<tr>
<td>$V_p$ dry sample:</td>
<td>2,155 [m/s]</td>
</tr>
<tr>
<td>$V_p$ saturated sample:</td>
<td>2,885 [m/s]</td>
</tr>
<tr>
<td>Cohesion:</td>
<td>2,495 [Psi]</td>
</tr>
</tbody>
</table>

Table 2: The experimental conditions used to drill the sandstone sample called “Gres Des Vosges” at the ARMINES-MINES ParisTech

<table>
<thead>
<tr>
<th>BIT</th>
<th>ROP (m/hr)</th>
<th>max WOB (TONNE)</th>
<th>RPM</th>
<th>Conf P [psi]</th>
<th>OBP [psi]</th>
<th>P_r [psi]</th>
<th>Mud P [psi]</th>
<th>Mud Type</th>
<th>Mud Temp [°C]</th>
<th>Rock Temp [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PILOT BIT + REAMER</td>
<td>4</td>
<td>1</td>
<td>90</td>
<td>2,900</td>
<td>2,900</td>
<td>0</td>
<td>2,900</td>
<td>WBM</td>
<td>20</td>
<td>80</td>
</tr>
</tbody>
</table>

Table 3: The experimental results in terms of MSE reduction for different equivalent distances between the pilot bit and reamer. Exp. ~ experiment; avg. ~ average.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>0</td>
<td>8.92</td>
<td>2.91</td>
<td>88</td>
<td>185</td>
<td>4.13</td>
<td>95</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>10</td>
<td>14.62</td>
<td>1.39</td>
<td>89</td>
<td>221</td>
<td>2.15</td>
<td>85</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>16.5</td>
<td>19</td>
<td>2.65</td>
<td>88</td>
<td>373</td>
<td>3.6</td>
<td>80</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>30</td>
<td>28.5</td>
<td>0.22</td>
<td>87</td>
<td>114</td>
<td>4.6</td>
<td>20</td>
<td>79</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>43.3</td>
<td>19.5</td>
<td>0.46</td>
<td>87</td>
<td>75</td>
<td>4.05</td>
<td>15</td>
<td>84</td>
<td></td>
</tr>
</tbody>
</table>