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Improvements in Perforating Performance in High Compressive Strength Rocks

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Abstract

The productivity of wells damaged during drilling is directly dependent on the depth of the damage and the performance of the perforating guns. If the perforations by-pass the damaged zone then the well will have a low mechanical skin. Conversely, if the depth of damage is greater than the perforation length, the skin factor will be much higher, especially when the drilling damage is severe. While we normally associate drilling damage with low strength rocks, there are reported hard-rock fields with extensive drilling damage.

The performance of shaped charges is significantly affected by the compressive strength of the rock to be perforated; consequently, the ability to bypass drilling damage in formations with high rock strength is reduced. Previously reported work[1,2] has shown a 75% reduction in total target penetration, compared to API Section I, in rock with an unconfined compressive strength of approximately 25,000 psi.

This paper describes the development and field testing of alternative charge designs aimed at improving performance in high compressive strength formations. So that the adverse effects of drilling damage can be reduced, computer simulations and laboratory tests showing the improvements achieved are presented. Field testing of the new charges and results achieved are shown.

Introduction

The basis for this project was to increase charge penetration depth to help optimize the completion efficiencies for the hard rock sandstone reservoirs in South America. Due to the unique properties of these quartz arenite sandstones, high compressive strengths up to 25,000 psi are common, and corresponding penetration depths are reduced. Additionally, these reservoirs have high permeability and modest porosities, resulting in large pore throats.

Formation damage often occurs during the drilling of a well. Exposure to a drilling fluid generally results in the invasion of the rock matrix by mud filtrate and by mud solids. The extent of this invaded zone is dependent on several factors, such as the fluid loss characteristics of the mud system, the applied overbalance, the pore size distribution of the rock matrix and the time taken to drill the zone. The invaded zone may range from a few inches to a few feet around the well and usually results in a reduction of permeability. This permeability reduction, or damage, can have a dramatic impact on the potential productivity of the well.

The most important consideration with respect to perforation length and well productivity is whether there is drilling damage and if the perforation length is sufficient to bypass such a damage zone. It is normally expected that effective perforating will bypass formation damage around a well if this damage is limited to a few inches. In hard rocks, the probability of bypassing the damaged zone is reduced due to the reduction in observed perforation length. For hard rocks with a significant depth of formation damage it is unlikely that the perforations will reach beyond the damaged zone.

The effect of perforation length on well productivity has been reported by McDowell and Muskat[3], Harris[4] and Klotz et al.[5] These studies showed that the well productivity could only be maximized if the perforations penetrated beyond the damaged zone. Even when only a few perforations just pass the damaged zone the observed impact on productivity is significant. Computer models, such as the method of Karakas and Tariq,[6] can be used to predict the impact of perforating parameters and drilling damage on the expected mechanical (Darcy) skin factor for a well.

Reservoir in-flow simulators showed that the combined reduction in penetration depth and the large depth of formation damage in the quartz arenite sandstone resulted in the perforations not extending beyond the drilling damage, resulting in low productivity. To regain productivity, a three step program was initiated: 1) reformulate the drilling fluid solids to reduce the depth of drilling damage; 2) increase charge penetration into hard rock, and 3) double the shot density. The later step could be immediately applied and has been effective as predicted by the in-flow simulators and shown in a recent paper.[7] Work on the design of drilling fluids to minimize damage in these sandstones has also been performed[8].

Perforating also produces debris in the created tunnel, consisting of crushed rock and the remains of the shaped charge liner. Liner debris is typically seen near the end of the tunnel and, if sufficient, may reduce productivity (and injectivity) compared to a clean perforation tunnel. A laboratory study of hard-rock perforating showed that, in the majority of tests, debris remained in the perforation tunnels, despite perforating with high underbalances. This reduced the effective length of the perforations, sometimes by as much as 50%[2].

Perforator Penetration Mechanics

Shaped charge perforators have been used in the oilfield for over 50 years. However, a detail understanding of the penetration physics is insufficient to predict penetration performance from first principles without the use of empirical data. In this section, we review our understanding of the effect of various reservoir parameters on penetration depth.

Concrete Targets. Oilfield perforators are qualified for penetration and casing hole diameter in surface concrete targets as specified in API RP 43 5th Ed.[9] Furthermore, most service companies use small concrete targets for quality control tests. As a result, over time, perforators become optimized for concrete. Thus, the question of optimum performance in harder rock is raised. Will a perforator optimized for penetration in concrete (or a weak rock) also perform optimally in a much harder rock? The short answer is no, and that is part of the focus of this paper, as well as the effects of the reservoir properties on formation penetration and the development of a deep penetrating charge optimized for hard rock.

Strength, Stress and Active Target Effects. Thompson[10] published the first paper showing the effects of rock compressive strength on perforator performance. Saucier and Lands[11] published the first paper demonstrating that the effective stress (average rock stress minus pore pressure) severely degrades penetration in rock. Continuing work on the stress effect by Halleck, et al[12-15, 1] showed that smaller charges were affected more than large charges and that weak rocks were affected more than strong rocks (concrete penetration is not stress dependent). During this same time frame, Behrmann and Halleck[16] showed that penetration in concrete, in addition to rock, was degraded by compressive strength.

An additional target effect exhibited by rocks, as opposed to concrete, was illustrated by Aseltine[17]. This is called an “active target” effect and is a result of a rock "reaction" which destroys portions of the perforator jet prior to its penetration into the rock. This effect was discovered during WW II and its many variants are used today to protect modern armored vehicles from shaped charge and projectile impact.

Rock Lithology. Rock lithology is another recently recognized variable affecting rock penetration. Perforating through layers of “weak” and “hard” rock reduces the penetration depth when compared to a homogeneous rock of the same compressive strength[2] . Data from the work of Ref. 2 was expanded and reported in Ref. 18. Additional analysis was performed on this data and is shown in Table 1. Calculations of the theoretical penetration depth were performed and compared with the experimentally observed values. CT-Scans of Targets BPC-3, -5’, and -8 showed dense (“hard”) layers of rock near the middle and end of the perforations. The ratio of experimental-to-theoretical penetrations averaged 0.69 for these three tests, whereas for the homogeneous outcrop Carbon Tan cores, CT-1, and -2 tests, this ratio was 0.96. Figs. 1 and 2 show CT-Scans of Tests BPC-5' and BPC-8 demonstrating the effect of hard rock layers on the penetration process. Note the reduction in hole diameter as the perforation passed through the hard layer, Fig. 1. Figure 2 shows that the penetration stopped and was diverted along a less dense (weaker) path when a hard layer was encountered. Although not seen in the gray scale CT-scan of Fig. 2, there is liner debris just after the open portion of the perforation.

Recent indications are that sand-grain size may also be an important determinate of rock lithology. Experiments using concrete targets[19] show that the size of the aggregate sand can affect penetration by 10% or more: Penetrations were deeper using targets made with finer-grain sands than with coarser-grain sands. The effect seems to relate to grain size alone and not to the compressive strength of the target, since the deeper-shooting targets had the same or slightly higher compressive strength.

Thus we see that rock lithology can severly impact the penetration process even with targets of equal strength.

Charge Development

For many wells, the relationship between perforation length and well productivity requires that improvements are made in either perforation damage skin and/or perforation length. Penetration flow tests in high compressive strength reservoir rock[18] showed that perforation damage skin for the most part was zero or negative. Due to the extensive depth of drilling damage, increasing effective penetration depth was the focus of this reported work.

QC Target. The first problem to be solved in the development of a “hard rock” charge was to select a QC target. A comprehensive perforator testing program by Exxon[20] clearly showed that the best perforators for concrete or steel were not necessarily the best for rocks (Figs. 3 and 4). However, other work[1] suggested that steel might be a good QC target for hard rock.

Due to the very high cost of hard natural rock targets, initial experiments were performed to evaluate steel versus hard rock QC targets. Figure 5 shows penetration time-of-arrival (TOA) data for steel and Nugget sandstone (UCS = 16,000 - 18,000 psi). Note that both the penetration “path” and final penetration values are different implying that steel will not be a good surrogate target. Fig. 6 further confirms this showing that penetration in rock may be more influenced by the explosive loading force than for penetration in steel.

As a result, the QC targets were Nugget sandstone 2.75 in. by 2.75 in. by 16-in. to 18-in. long backed up with a QC concrete target. These targets were cemented into a 6-in. sonotube and then placed into a steel “C-clamp” to simulate an infinite thick target, Fig. 7. If the target was not placed in a steel clamp, total penetration would have increased approximately 20% to 40%. The Nugget was vacuum saturated with brine and maintained in a saturated condition until shot. Penetration was perpendicular to the Nugget bedding plane. Inconsistent and deeper penetrations were obtained when charges were shot parallel to the bedding plane.

Charge Optimization. A combination of computational, analytical and instrumented tests are used to understand, first, the physics of jet formation and, second, the jet/target interaction. The Autodyn™ finite difference code is used to calculate the jet velocity and mass versus time/position[21]. Penetration TOA tests are conducted to obtain jet quality and dynamic target properties. These test data with the Autodyn™ results are then used in an analytical penetration code. Finally, X-rays of the jet versus target penetration are used to help determine the "active" target effect which is then used to update the penetration model. Design iterations are then performed to obtain an optimum design.

Experimental - Theoretical Design Results. X-rays of the residual jet versus target thickness were also used to obtain the jet velocity and penetration time versus target penetration. These data were then compared with theoretical calculations using both Autodyn™ and penetration simulations. Two simulations were used with different explosive equation-of-states to represent design/production uncertainities.

Figure 8 shows the comparison between experiments and theory for the penetration-time-of-arrival for the final design. (The final experimental penetration was 15.9"; its time-of-arrival is not shown since it is usually not obtainable.) Three theoretical models are also shown. Models One and Two are for different explosive equation-of-states with active target considerations, whereas Model Three does not account for the "active" target effect.

Interpretation of Fig. 8 shows that Theoretical simulation One matched the early experimental jet velocity/penetration up to a penetration depth of about 6-in.. The deviation in the TOA between experiment and theory after 6-in. suggests either a stronger active target effect than used in the simulator or higher jet velocities than shown experimentally. Theoretical simulation Two suggests an early jet velocity lower than shown experimentally, but a closer match of the tail portion of the jet velocity. Both simulations used the same active target parameters and the static UCS in the penetration model. The curve labeled Theoretical Three used the Autodyn™ simulation of curve One, but ignored the active target effect in the penetration simulator. To obtain the same theoretical penetration, the rock strength was increased from 1.2 Kbar to 7 Kbar, which is unrealistic and again demonstrates the need to duplicate the experimental penetration TOA.

Performance Results. A production baseline 34 g. charge was chosen for hard rock optimization before optimizing. This charge had an overall penetration in the Nugget sandstone of 12.6-in., which included a 3/8-in. steel face plate. The first optimized design was restricted to a liner geometry change only, the liner material and case geometry were those of the original production charge. The average penetration for this first optimized charge was increased to 14-in. as measured from 30 QC shots during an 8000 unit production run. The 14" was short of our goal of 16-in., thus, the only restrictions on the next design was to maintain the outer case geometry and liner material. This second design reduced the explosive charge from 34 g. to 30 g. and reached an average penetration of 15.9-in. from 14 QC shots in a 3000 unit production run.

Field Results

To date, a limited number of field trials have been performed. The hard-rock charges have been used on both oil producers and gas injectors, but quantitative data regarding their performance have not been obtained. Qualitative data in one field suggests an improvement in performance has been achieved: a gas injector perforated at 4 shots per foot is outperforming the majority of gas injectors in the field which were shot at a higher shot density (up to 12 shots per foot). Although reservoir quality could also be the cause of the higher performance, the estimation from logs is that this well is similar to the other gas injectors in the field. It is therefore likely that it has a lower than average skin factor. A similar result has been observed on an oil producer, which is on production at a shot density of 4 shots per foot, compared to a typical shot density of 8-12 shots per foot for other wells in the field.

It is hoped that quantitative data of the performance of hard rock charges will be obtained in the near future. In addition, field trials of the latest charge design will commence shortly. These charges should provide a further improvement in performance.

Conclusions

1. Perforating penetration in high compressive rocks can be increased by optimizing the perforator geometric design.
2. The penetration physics of oil field perforators into rock is only partially understood and semi-empirical analysis is still required.
3. A substitute QC target for hard rock has not been found.
4. Qualitative field data confirms an increase in well productivity/injectivity.

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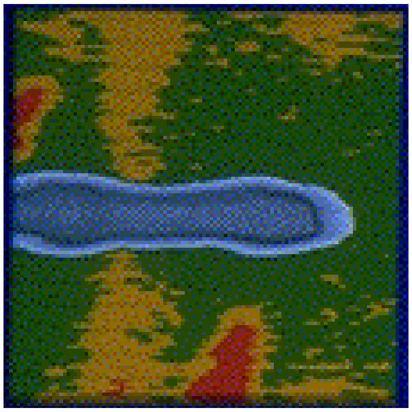

Figure 1 Test 5' From SPE30082
The light colored regions are high density rock

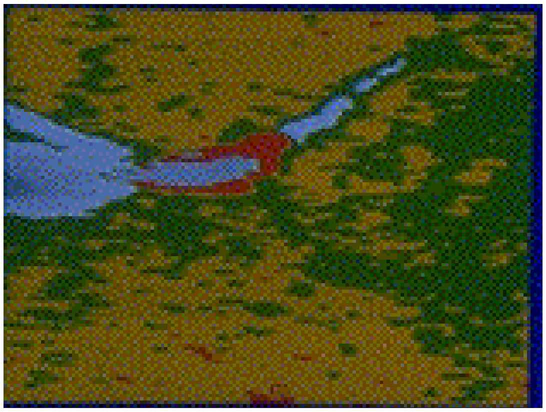

Figure 2 Test 8 from SPE 30082
The light colored regions are high density rock

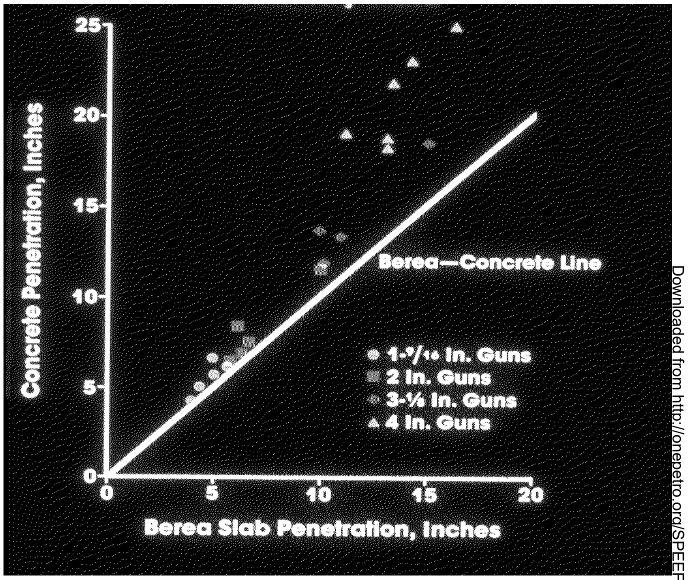

Figure 3 Concrete versus Berea slab penetration data

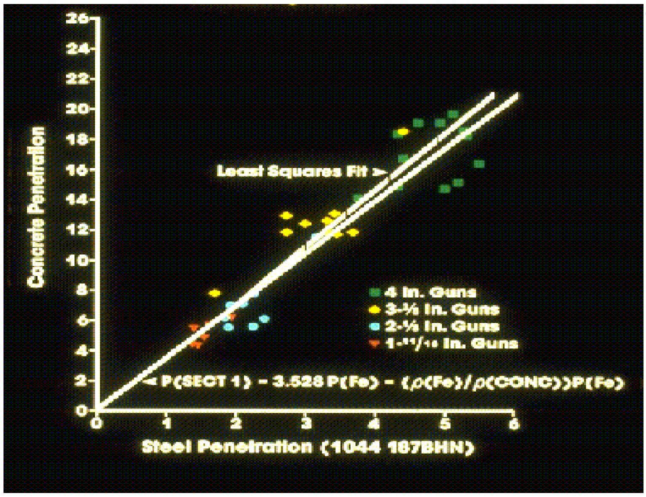

Figure 4 Concrete versus steel penetration

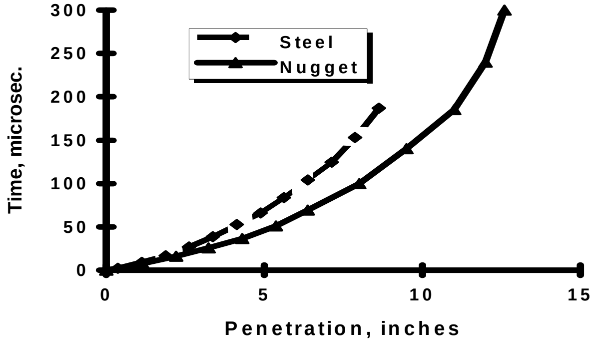

Figure 5 Penetration time-of-arrival

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