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Investigation of the Influence of Pressures and Proppant Mass on the Well Parameters after Hydraulic Fracturing

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ABSTRACT

This paper considers the implementation of hydraulic fracturing in an oil field located in the Arkhangelsk region in Russia. During the exploitation, the production rates and injectivity of the injection wells in the field were intensively decreased. To increase well flow rates, hydraulic fracturing of the formation was carried out, and the evaluation of the efficiency was performed. Oil production rates after the fracturing increased 3.2 times and the productivity index increased twice. The influence of the geometrical sizes of fractures on the volume of injected proppant was investigated. An increase in the mass of the injected proppant from 2 to 3 tons per 1 meter of formation thickness leads to an average increase in the crack width by 0.5 mm, and the half-length by 40 m. Well work parameters after hydraulic fracturing of a reservoir were obtained as a function of the original parameters of the reservoir. It was observed that there is a sharp decrease in well production rates after fracturing in wells with low bottom hole pressures. When the pressure at the bottom of the well decreases from 60 to 20 MPa, it leads to an average decrease in the crack width by 2 mm, and the half-length of the crack by 50 m. Direct correlation between the well productivity coefficients after fracturing and the values of bottom hole pressures was observed. The optimal conditions for fracturing were identified, which made it possible to significantly increase the efficiency of the operation.

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NOMENCLATURE

P_r	Production rate (t/day)	P_{sat}	Saturation pressure (MPa)
F_r	Flow rate (m^3/day)	PI	Productivity index
P_{bot}	Bottomhole pressures (MPa)		

1. INTRODUCTION

During field development projects for oil fields, especially those characterized by a branched network of cracks, the location of the wells over the area of the deposit needs to be carefully considered as the optimisation of wells location and the interaction of natural and artificial cracks allows increasing the oil production from the reservoir [1].

It is known that the compensation of reservoir volumes of produced fluid by injected volumes of water ensures the consistency of reservoir pressure. As a consequence, relatively stable oil well production rates are maintained, but in the course of time the content of water in the produced fluid increases. However, for waterflooding of low-permeability reservoirs, this condition is often not fulfilled for the following reasons [2]:

- Insufficiently effective transfer of the impact from the injection zone to the selection zone leads to a decrease in reservoir pressure in the drainage area, even if the compensation condition is formally observed.
- The situation is exacerbated by the use of intensive oil production systems based on wells with cracks of considerable length fracturing, horizontal wells with multi-zone fracturing (several cracks from

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different points of the trunk), etc., to develop low-permeability layers.

Successful practical application of hydraulic fracturing technology is not possible without taking into account existing geological and technological limitations [3].

Geological limitations are those which are related to the features of the geological structure of the reservoir and the underlying layers above and below [4, 5, 6, 7]. For example, the proximity of gas or aquifers (less than 10 meters) leads to the need to limit the growth of the crack in height, which automatically leads to the limitation of the maximum volume of the injected proppant, and requires a change in the perforation strategy and a hydraulic fracturing design [8, 9]. Also, geological restrictions can be conditionally referred to the limitations associated with the organization of waterflooding. Decrease in rock brittleness inhibits fracture propagation and lower minimum horizontal stress contrast leads to fracture containment [10, 11].

Technological restrictions include restrictions related to the technical capabilities of the equipment and chemical reagents used [12, 13, 14, 15]. For example, the presence of a restriction on the maximum pressure developed in the process of hydraulic fracturing (primarily due to the capability of wellhead reinforcement and the power of pumping units) can lead to the limitation of the maximum width of the crack.

The highest efficiency of hydraulic fracturing can be achieved by designing its application as an element of the development system, taking into account the well placement system and evaluating their mutual influence in various combinations to treat producing and injection wells in modern software products such as WellFrac, FracPro, Mfrac, StimPt, Petrel, and others. The effect of hydraulic fracturing is not uniformly manifested in the operation of individual wells; therefore, it is necessary to consider not only the increase in the production rate of each well due to hydraulic fracturing, but also the effect of the mutual arrangement of wells, the specific distribution of reservoir heterogeneity, and the energy capabilities of the facility.

In the subject literature, it is noted that such parameters of the technological process of hydraulic fracturing as injection rate of fluid [16], the volume of proppant [17], and applied pressure significantly affect the efficiency of the operation. Nagar et al. [18] noted that the longitudinal cracks in the rocks increase the well production rate more significantly than transversal ones. Therefore, the parameters of fracturing need to be selected, taking into account the geological and physical conditions of the deposit.

The current work aims to investigate different measures to increase the efficiency of hydraulic fracturing in a field focussing on

- analysis of the original conditions and results of the fracturing on the wells;
- definition of the refined criteria of wells selection for carrying out hydraulic fracturing;
- determination of well-working conditions after hydraulic fracturing.

This paper is organised as follows. In the next section, the considered oil field and characteristics of the deposit are described. The field infrastructure and history of operation including the encountered difficulties are detailed in the following section. The performed hydraulic fracturing and analysis of the results are given in section 4 and finally concluding remarks are presented.

2. RESERVOIR INFORMATION

The oil field analysed in this study is located in the southern part of the Nenets Autonomous District of the Arkhangelsk Region. In tectonic terms, the deposit is confined to the central part of the Kolvin megaval. The main oil reserves are confined to the sandstones of the Middle Devonian (D_2st). The oil is light, low-viscosity, the permeability of the collectors is quite high. The oil production of the wells during their operation is significantly reduced, and the water injection is used to enhance the oil recovery. To increase oil production and the volume of injected water, hydraulic fracturing of the formation is actively carried out in the fields. However, during fracturing, well flow rates often decrease significantly and the planned oil production levels are not reached.

The terrigenous deposits of the Old Oskol overhorizon of the Middle Devonian D_2st are represented by sandstones of monomineralic quartz small-medium-grained, medium-coarse-grained and heterogeneous grains, aleurosandstocks, siltstones with various grained, argillites fractured; micro profile is found enriched with fragments of psephitic dimension (gravel-sandstone). Macroscopically the rocks of these sediments are light gray, gray, plot up to a dark gray color, with a brownish tinge, due to uneven oil saturation, strong, dense, porous, stylized, and fractured to varying degrees. The rocks are unevenly carbonized, pyritized, and sulfated**.** In the section of rocks, quartz fine- and medium-fine-grained sandstones are permeable. The basic information about the parameters of the deposit is given in Table 1.

The reservoirs in the deposit have medium porosity, average permeability values, high-gas-saturated and low-viscosity oil. Saturation pressure high values of oil with gas and the initial reservoir pressure are worth being noted.

TABLE 1. D_2st oil reservoir Geological and physical characteristics

Parameters	Value
Depth, m	4129…4084
Type of collector	terrigenous
Effective oil-saturated thickness, m	5.20 -19.5
Coefficient of porosity, fractions of units	0.087- 0.096
Permeability, 10^{-3} μm^2	13.6 - 60.7
Initial reservoir temperature, °C	102
Initial reservoir pressure, MPa	44.3 - 51.8
Viscosity of oil in reservoir conditions, mPa·s	0.69 - 0.81
Oil Density in reservoir, t / m^3	0.690 - 0.705
Oil Density in surface, t / m^3	0.818 - 0.822
Volume factor of oil, fractions of units.	1.36 - 1.42
Oil saturation Pressure, MPa (P_{sat})	18.1 - 23.9
Gas factor, m^3 / t	164.3 - 169.1

Reservoir D_2st (sandstone of the Layer of the Middle Carboniferous Tier) has been put into trial operation in April 2001 by one exploratory well.

In 16 years from the beginning of production, there were 31 wells in the production fund, including 25 units in the current fund. The average daily oil production rate for the wells was 78.1 tons per day. The active injection stock was 3 units.

The period from 6 to 9 years from the beginning of production was characterized by a decrease in the selection of liquid and oil, which was due to a decrease in reservoir pressure in the oil extraction zone, as well as the retirement of four wells into inactivity. The watercut of the production for the same period has remained stable and amounts to 0.4%.

The period from 10 to 11 years from the beginning of production was characterized by a positive dynamics growth in the extraction of liquid and oil, which was due to the introduction and effective operation of the pressure maintenance system.

The operating fund of production wells in 12 years compared to 11 years did not change. But oil production decreased by 30%, the production of liquid by 37%, watercut decreased to 1.9% (the fact of 2011 - 6.7%). The main problems of the development of this facility were:

-Weak coverage by area (the northern and southern parts of the deposit are not involved in the development);

-Anticipatory watering of wells by pumped water through the most permeable interlayers;

-Heterogeneity of the reservoir (the flow rate of the fluid varies significantly in the wells);

-Presence of sites with low reservoir pressure (in the main selection zone). The average weighted reservoir pressure in the extraction zone is 32.3 MPa, which is lower than the initial reservoir pressure by 37.8%. The saturation pressure along the reservoir is 18 MPa;

- availability of a non-working well stock.

In 16 years from the beginning of production, the current oil recovery was 19.2%. The selection from the initial recoverable reserves was 42.75%, with an average watercut for 2016 - 28.3%.

The productive layers of the oilfield were developed with the maintenance of reservoir pressure by flooding. Current and accumulated compensation for the field amounted to 74.5% and 52.5% respectively.

In the period from 10 to 11 years, oil production rate was growing, which is connected with the effective operation of the pressure maintenance system and the results of the measures to increase production rates. But after the 12-year production, the oil production rate began to decline. The increase in watercut for the period under review was 25%.

From 14 to 17 years of production, the following measures were carried out at the field: repair and insulation works were carried out in 4 wells, optimization was performed in 7 wells, 1 reperforation, and 23 fracturings.

Based on wells performance data obtained in the selected field in the results of hydraulic fraction operation, this paper aims to evaluate the efficiency of hydraulic fracturing and develop recommendations for optimizing hydraulic fracturing.

4. HYDRAULIC FRACTURING RESULTS

The main factor that determines the necessity of hydraulic fracturing in wells is the failure to achieve the oil production expected according to the well drilling regulations (known reservoir properties). Low well productivity is usually associated with damage to the bottomhole formation zone caused by the action of the drilling fluid during drilling, blockage of the pores during operation, and the shutdown of wells during underground and overhaul repairs [19, 20]. Low productivity of wells can also be associated with low reservoir properties of the bottomhole formation zone. It is also possible to reduce the permeability in the bottomhole zone due to the deformation of the collectors having high clay content and subject to the highest pressure drops in the bottomhole zone. Therefore, when planning the hydraulic fracturing, an important task is to assess the reason for not obtaining the design parameters of oil production in specific wells.

To increase oil production during years 14 to 17 of operation, hydraulic fracturing of the formation was carried out on 23 wells. As the fracturing fluid, gels with a gellant type DWP-991 and a stitcher type DWP-114 were mainly used. The mass of proppant injected into the reservoir varied from 12 to 78.5 tons. In most cases, proppant type BoroProp was used. The average fracture pressure at fracturing was 52 MPa. The average values of the parameters of the formed fracture cracks were as follows: crack opening - 1.8 mm, height - 15 m, half-length - 164 m.

The main indicators of the wells before the activities and in the first month after the fracturing are given in Table 2.

In the field, oil production rates after the fracturing increased 3.2 times, productivity index increased 2 times. The average watercut of wells increased from 29.88% to 30.81%.

The wells were operated at average reservoir pressures mainly slightly below the gas saturation pressure. The bottomhole pressure after fracturing was 0.6 to 1.5 relative to saturation pressure. The specific gas content of the oil in the free gas in the reservoir at the walls of the wells at the lowest bottomhole pressures reached 0.5. At such gas content values, the relative permeability of rocks over oil can decrease several-fold.

TABLE 2. The main parameters of wells operation (average values)

Parameters	Before frac	After frac
Flow rate, m^3 / day	32.6	88.35
Oil production rate, t / day	15.88	52.22
Watercut,%	29.88	30.81
Reservoir pressure, MPa	27.42	27.42
Bottom-hole pressure, MPa	17.45	23.68
Productivity index, m^3/(MPa·day)	3.01	6.29

To increase the flow rate in the well 609 located in the area of the injection well (Figure 1) hydroulic fracturing was conducted. However, the reservoir pressure in its area was reduced by 20% of the initial value. During hydraulic fracturing, it was very important that the fracture does not propagate towards the injection well. Therefore, to ensure the success of the process, the hydraulic fracturing was planned using modern software products with the construction of the conductivity profile. With the decrease in Biot coefficient, stress inversion region will decrease significantly [21]. The pump flow increases and the crack deflection distance increases [22]. The pre-fracturing parameters were as follows: Reservoir pressure– 39.6 MPa; Bottom pressure– 14.6 MPa; Productivity index - 0.96 m^3/(day·MPa); Flow rate - 23.9 m^3/day; Oil production rate - 18.8 t/day; Watercut - 0%. Parameters after frac: Bottom pressure - 14.8 MPa; Productivity index - 24.8 m^3/(day·MPa); Flow rate - 69 m^3/day; Oil production rate - 40.7 t/day; Watercut - 10%.

The results showed that appropriate choice of fracturing technology and parameters has been made demonstrating improve production rate.

5. ANALYSIS OF RESULTS AND DISCUSSION

Hydraulic fracturing allows to increase the well production rate by creating highly permeable channels. The size of the channels depends on the mass of the proppant injected and the pressure in the reservoir.

The effectiveness of hydraulic fracturing can be traced by the change in the productivity index. However, the productivity index immediately after hydraulic fracturing can increase and then sharply decrease due to deformations of productive formations, gas release and deposits of wax and salts.

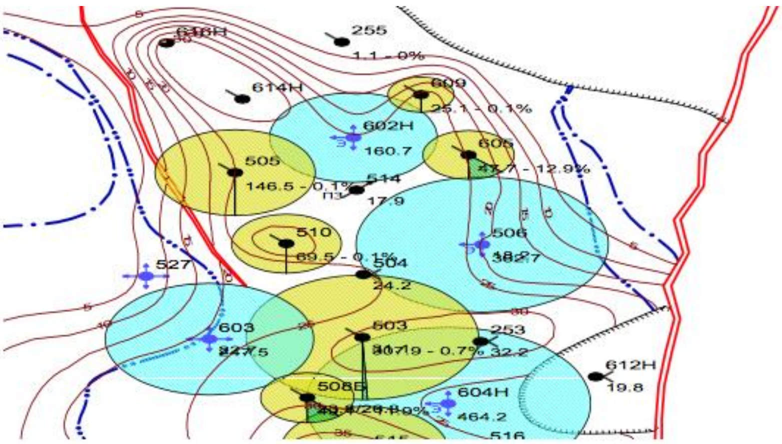


Figure 1. Well 609 location plan

The dependence of the productivity index on the ratio of bottomhole pressure and saturation pressure was analyzed and the following equation of the productivity index after fracturing depending on the relative bottomhole pressure was obtained:

$$PI = 4.4\ P_{bot}/P_{sat} + 0.14 \quad (1)$$

For the considered interval P_{bot}/P_{sat} 0.6-1.5, the correlation coefficient of the linear dependence was 0.95.

The duration of the effect from the fracturing was 16 months. After fracturing, productivity index and production rate of the well began to decline rapidly. For 16 months after hydraulic fracturing, the flow rate of the well has decreased from 1.2 (relative to the original) to 0.5. This can be associated with low bottomhole pressure in wells, which values are in the range of 0.6 from the saturation pressure.

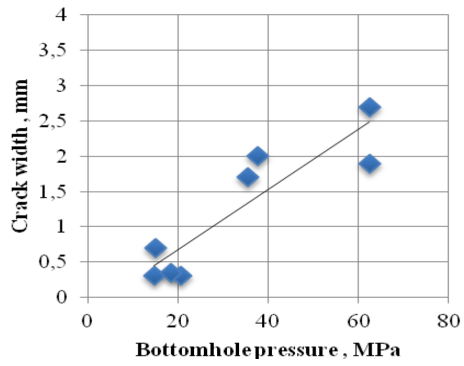
Dependence of crack width and half-length of cracks of the field D_2st object after the fracturing on the bottomhole pressure is shown in Figure 2. It can be noted that there is a clear relationship between the bottomhole pressure after fracturing and the well productivity factor. This ligature is caused by deformations of rocks [23] with a decrease in reservoir pressure and release of free gas at bottom pressure below the saturation pressure.

Using the value of reservoir pressure, the production wells can be divided into two groups: with the formation pressure in the drainage area greater than the saturation pressure and with the formation pressure less than the saturation pressure. Wells with reservoir pressure above the saturation pressure are characterized by the largest increase in oil flow rates and the duration of the effect from the event. It is noted that the dynamics of productivity coefficients in the operation of wells after fracturing depends significantly on bottomhole pressure. With a decrease in bottomhole pressure and an increase in depression in the reservoir, the coefficients of well productivity decreased, well flow rates neither increased or slightly decreased. With the increase in bottomhole pressure after fracturing, the productivity factor and oil rates increased.

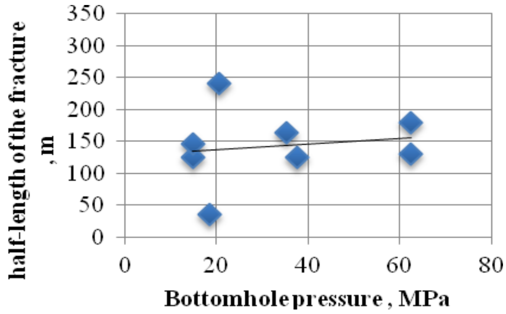
Pressure values also affect the size of cracks occurring during the fracturing process (Figures 2 and 3). The number of cracks depends on how effectively hydraulic fracturing was performed. In this case, the width of the cracks increases with increasing reservoir pressure and saturation pressure ratios [24].

With a decrease in saturation pressure and an increase in reservoir pressure, the ratio on the whole increases, the size of the crack increases, and as a result the effective hydraulic fracturing is performed [25, 26].

The dependence of the geometric dimensions of the formed cracks on the mass of the injected proppant per



(a)

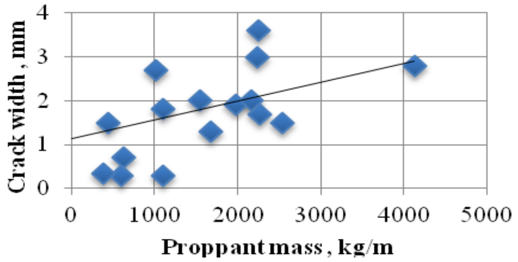


(b)

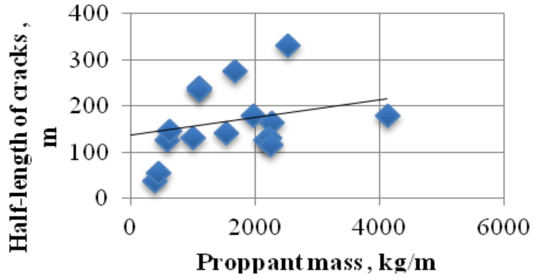
Figure 2. Dependence of crack width (a) and half-length of cracks (b) after fracturing on bottomhole pressure

1 meter of perforated thickness is shown in Figure 3. As the concentration of the wedging element increases, the crack width on the average also increases. It can be said that as the proppant mass is increased, the size of the cracks increases, which leads to a good result. In some cases, the formation of plugs is possible, so the determination of the proppant concentration should be made taking into account all other factors, such as the injection rate, the volume of the fracturing fluid, the quality of the wedging element [27, 28]. As the volume of injected proppant increases, the openness and half-length of the cracks increases. The cost of the fracturing work is determined by the feasibility and environmental impact assessment. Fracture indicators are usually evaluated depending on the length of cracks. The cost of work on hydraulic fracturing increases with the length of the crack. The income curve without the cost of hydraulic fracturing has a maximum at some length. The optimal value of the proppant mass per meter of perforated thickness for the deposit is 2 t / m. This volume of the proppant ensures the most optimal cracks both from the point of view of technological efficiency and costs [29, 30].

The longer the crack is, the larger the inflow from the formation to the fracture is. But at the same time, the



(a)



(b)

Figure 3. Dependence of crack width (a) and half-length of cracks (b) after fracturing on proppant mass per 1 meter of perforated thickness.

crack becomes narrower, and the cross-sectional area decreases, and for some values of its conductivity, the crack begins to play the role of a chimney [31]. As a result, the pressure drop in the crack increases. Accordingly, the effective pressure drop between the fracture and the formation decreases. That is, with the growth in the fracture length there are two opposing factors: an increase in the area of inflow to the fracture, increasing the production rate of the well, and a decrease in the effective pressure drop between the fracture and the formation, which reduces the production rate of the well. Consequently, for a fixed fracture volume, there is a ratio of the half-length of the fracture and its width at which the flow rate of the well is maximized.

The intensive development system implemented in the field is far from realizing its potential due to the lack of efficiency of pressure maintenance system. In such conditions, the medium- and long-term dynamics of the production rates, especially for wells with hydraulic fracturing, is determined not by their productivity, but by the possibilities of compensating the volume of fluids taken out of the formation. Based on the results of the analysis it is possible to give a presumed efficiency estimate for other wells in which the action is only planned.

The conducted study confirms that the selection of candidate wells for the application of the hydraulic fracturing technology has to be carried out according to the following criteria [32, 33]:

- current reservoir pressure is not lower than the gas saturation pressure;
- effective oil-saturated thickness is not less than 3.5 m;
- the thickness of the dense bridge is more than 3 m;
- the tightness of the production column and the absence of streaked flows;
- a satisfactory state of the cement stone in the perforation interval.

According to the results obtained the optimal conditions for hydraulic fracturing in the field under consideration are: maintaining bottomhole and reservoir pressure above the saturation pressure, specific proppant flow rate - about 2 t/m, proppant type – BoroProp.

6. CONCLUSION

The paper presents the results of hydraulic fracturing study conducted in the field located in the southern part of the Nenets Autonomous District of the Arkhangelsk Region in Russia. When analyzing the work of the well stock, it was noted that well flow rates were intensively decreasing due to the deformation of rocks and release into the free phase of dissolved gas in the oil. Large depth of wells with relatively low permeability values led to the fact that wells after construction and repair were hard to put into operation.

In order to improve the oil production, hydraulic fracturing has been actively used in the field. When analyzing the technological efficiency of hydraulic fracturing, a significant relationship between the geometric parameters of cracks and the energy state of the formation in the borehole region was revealed. An increase in the mass of the injected proppant from 2 to 3 tons per 1 meter of formation thickness leads to an average increase in the crack width by 0.5 mm, and the half-length by 40 m. Analogous relationships also exist in the evaluation of the productivity and production rates of wells after fracturing. When the pressure at the bottom of the well decreases from 60 to 20 MPa, it leads to an average decrease in the crack width by 2 mm, and the half-length of the crack by 50 m. The optimal conditions for hydraulic fracturing in the considered field were achieved by maintaining bottomhole and reservoir pressure above the saturation pressure, using a specific proppant flow rate at about 2 t/m for the selected proppant type (BoroProp). Based on the obtained dependencies, it is possible to predict the results of hydraulic fracturing in the field. For example, if we carry out a fracturing operation taking into account the above recommendations, we will increase the oil production rate by about 20%.

7. ACKNOWLEDGEMENT

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Persian Abstract

در این مقاله اجرای شکستگی هیدرولیکی در یک میدان نفتی واقع در منطقه ارخانگلسک در روسیه مورد بررسی قرار می گیرد. در حین بهره برداری ، میزان تولید و تزریق چاه های تزریق در مزرعه به شدت کاهش می یابد. برای افزایش سرعت جریان چاه ، شکست هیدرولیکی سازند انجام شد و ارزیابی کارایی انجام شد. نرخ تولید روغن پس از شکستگی 3.2 برابر و شاخص بهره وری دو برابر افزایش یافت. تأثیر اندازه های هندسی شکستگی بر روی حجم غلاف تزریق شده بررسی شده است. افزایش جرم غلاف تزریق شده از 2 به 3 تن در هر 1 متر ضخامت تشکیل منجر به افزایش متوسط عرض ترک 0.5 میلی متر و نیمه طول 40 متر می شود. پارامترهای خوب کار پس از شکست هیدرولیک مخزن به عنوان تابعی از پارامترهای اصلی مخزن بدست آمد. مشاهده شد که پس از شکستگی در چاههای با فشار سوراخ پایین ، کاهش شدیدی در میزان تولید چاه وجود دارد. هنگامی که فشار در پایین چاه از 60 به 20 مگاپاسکال کاهش می یابد ، منجر به کاهش متوسط عرض ترک 2 میلی متر و نیمه طول ترک 50 متر می شود. همبستگی مستقیم بین ضرایب بهره وری چاه پس از شکستگی و مقادیر فشار سوراخ پایین مشاهده شد. شرایط بهینه برای شکستگی مشخص شد ، که امکان افزایش قابل توجه کارایی عملیات را فراهم کرد.