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Abstract

This paper presents an effective EOR solution for the development of oil-rim deposits. A case history is presented where production from a mature field with low permeability terrigenous reservoirs and nearby water and gas-cap was recovered without the drilling of new infill wells. Fracking in such conditions was not appropriate due to the close proximity of the gas cap. Directional radial drilling was used to accurately drill four channels in the required azimuthal directions before slotted liners were deployed in each channel to control solids production.

The directional radial drilling technology is unique and creates channels with a diameter of 69 mm (2-3/4”) and a length of up to 25 m (82 ft.) through the identified target zone in the reservoir. The special bottomhole assembly (BHA) is deployed on jointed pipes using a standard workover hoist. The stimulation method drills up to 4 hyper-short-radius channels from the same TVD, and formation evaluation measurements can be taken in each channel. Slotted liner or screens can also be deployed if required. This technique is ideal for thin low permeability reservoirs of any type.

A candidate well was identified and four channels with a diameter of 69mm (2-3/4”) were accurately placed at the same TVD along a pre-set trajectory in a radial pattern up to 14 m (46 ft.) per channel using a BHA with a mud motor. The planned-versus-actual trajectories were confirmed by a directional survey. A sand screen was deployed in each channel to control produced solids. The resultant performance of the target reservoirs was evaluated by the results of logging (inflow profile). An 898% increase versus the pre-operation production rate was achieved. A production rate with a liquid flow of 673 bbl. per day and an oil flow rate of 252 bbl. per day was obtained. Further reductions of water cut from 56% to 1% during clean-up, and the oil production rate was increased to 598 bbl. per day from the original 60 bbl. per day. The longevity and value of this EOR method is demonstrated by >16 months decline rate to return to initial production rates. The experience demonstrates that the technology is a very valuable stimulation method where gas cap and/or underlying water create challenges to conventional stimulation or infill sidetracking.

This was the first occasion this unique Directional Radial Drilling EOR technology was applied on an oil

deposit in a terrigenous reservoir. Additionally, this was the first-time the radial channels were lined with sand screens. The operation performed has proven that the technology of directional radial drilling is an extremely valuable EOR stimulation technique for oil wells where standard hydraulic fracturing is restricted. This technique is valid for and applicable to all reservoir types.

Introduction

The field under study is oil and gas condensate. It is located on the Yamal peninsula. The field was explored more than 50 years ago when the first gas flows were obtained from the exploration well. Full field development only began less than 10 years ago.

Several reservoirs were discovered in the field. They are mainly marine and coastal sandstones, with some silts and shale. The net pay of the reservoirs varies between 3 and 8 m.

The development of these low-permeability reservoirs is mainly carried out by drilling horizontal wells in the part of the oil rim.

In addition, the field is in a very remote location with tough climatic conditions (in winter the air temperature drops to 55 deg C below zero) complicate oil production at the field.

Goal and tasks

The study goal was to increase the efficiency of oil rims development and to maintain production in a field with complex geology.

An additional goal was to analyze the effectiveness of the new directional radial drilling technology:

1. Confirmation of the ability to directional drill radial channels with less than 10% deviation from plan.

2. Confirmation of the ability to install sand screens in the radial channels in a low-permeability reservoir.

3. Confirmation of productivity index improvement and oil production increase based on the results of the directional radial drilling.

The following objectives were set to identify targets and perform the operation:

- Analyze the available information about the reservoir, the well production history and its technical condition;

- Assess the prospects of using radial drilling in candidate wells;

- Design trajectories of four radial channels;

- Provide directional radial drilling at different depths of four radial channels;

- Confirm the ability to directionally survey each channel.

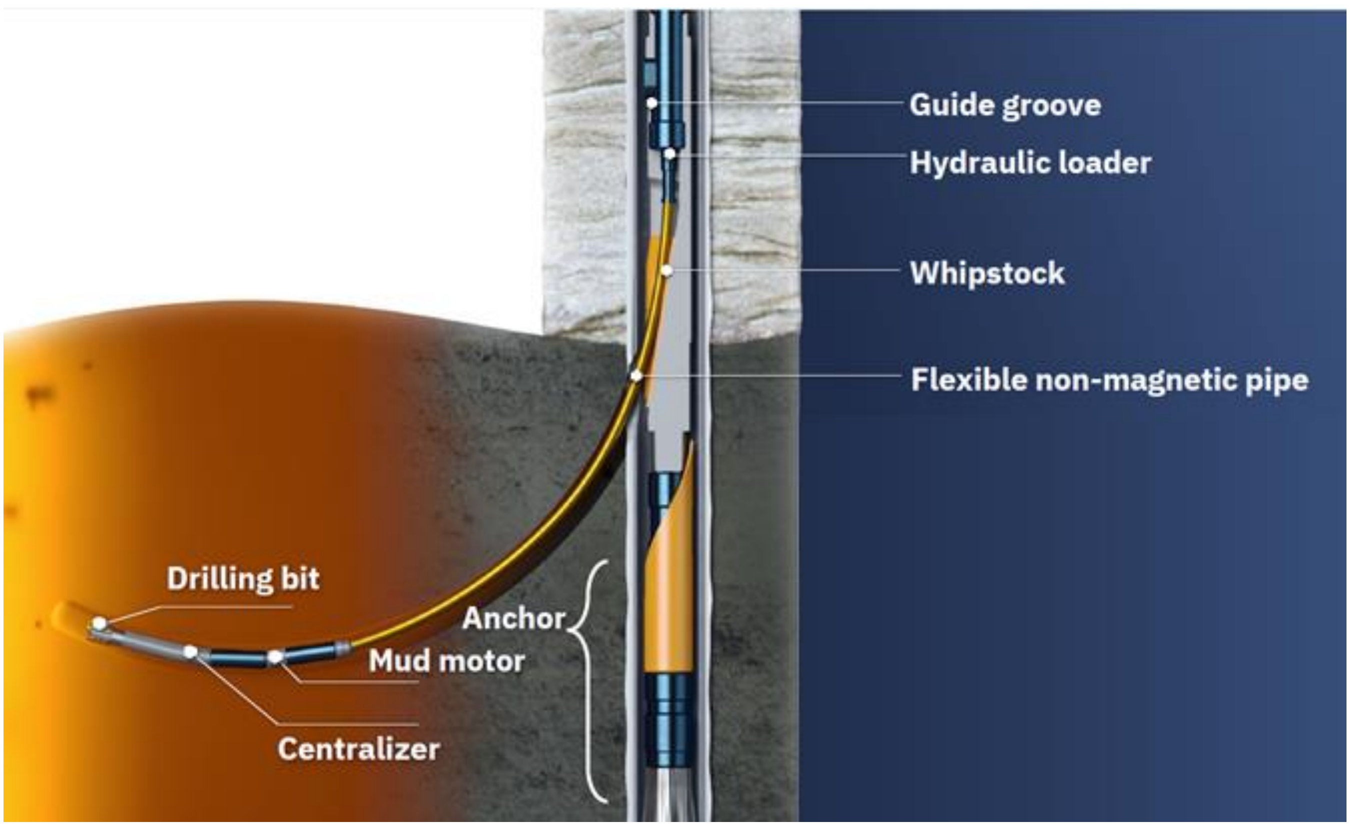
- Confirm the possibility of installing special slotted liner inside the drilled channels (as part of the Directional Radial Drilling System) for its casing;

- Compare the trajectories of the actual drilled channels with the planned trajectories;
- Perform a performance comparison of the new proposed technology of directional radial drilling with the results of conventional perforation techniques.

Methods and technologies

The Directional Radial Drilling System is a technology that uses special small-sized custom-built downhole motors. The technology allows drilling of radial channels up to 25 m long, with up to 4 channels located within one depth, with the number of such depth is unlimited, i.e., sets of channels can be "stacked" above each other in either cased or open hole and any well inclination from vertical to horizontal

The main elements of the Directional Radial Drilling System (Fig.1) are: a pipe to push the tool, connected to a BHA running tool, and a guide device at the bottom. It is connected to a hydraulic thruster to flexible non-magnetic pipe to a small-sized custom-built downhole drilling motor and a drill bit or mill. A special whipstock is contained in the BHA running tool which engages an orientation and anchor module set below the planned window depth [1-3]. No directional drillers are required for the drilling of the channels.



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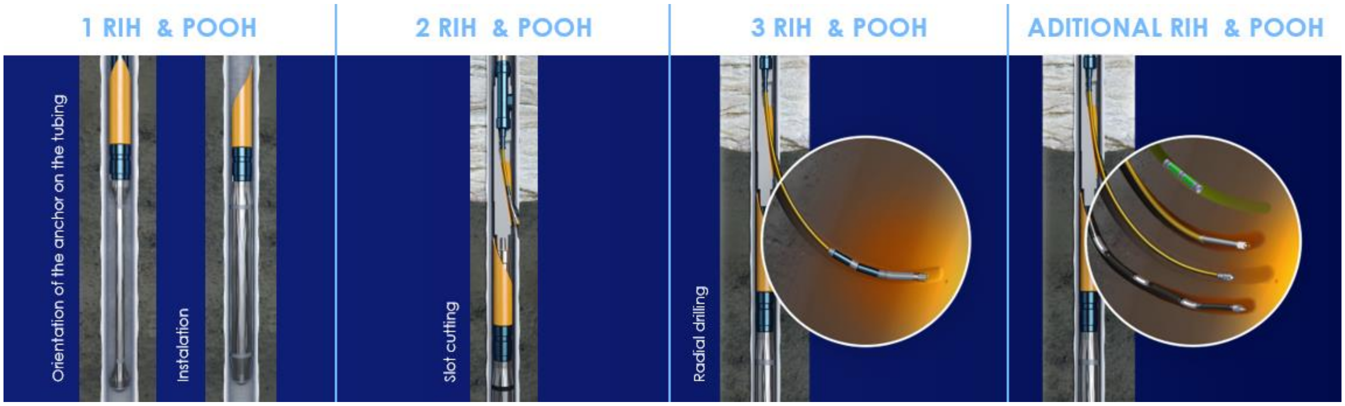


b

Figure 1 – The main elements of the Perfobore system for radial drilling (a) and the sequence of operations (b)

Stages of directional radial drilling:

1. The running and orientation of the anchor. After RIH, the anchor is positioned in depth using gamma ray and collar locator and set. The azimuth of the orientation guide is measured.

2. Window cutting. The cutting module is oriented to the correct azimuth at surface and lowered into the well, engages the anchor module and is oriented by the orientation shoe. After cutting the window, the cutting module is lifted out of the well.

3. Radial channel drilling. The drilling module is oriented at surface and lowered into the well and connected to the anchor module. After drilling the channel, the drilling module is lifted out of the well.

4. Directional survey, GR, electricity logging / deploying of the slotted liner / hydrochloric acid treatment can now be performed as required.

The main advantages of the technology are the accurate placement of the channel and the ability to re-enter into channels.

Experience of directional radial drilling's implementation in a low-permeability reservoir

To analyze the effectiveness of radial drillings in a low-permeability reservoir, a set of operations was performed in two wells.

Fig.2 shows a part of the analyzed field with the location of one of the wells, on which a directional radial drilling operation was carried out in Well N.

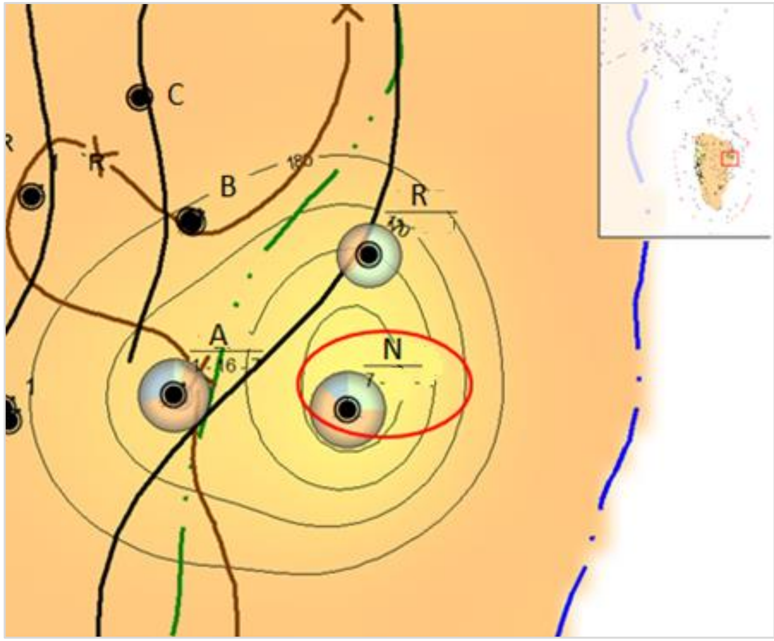


Figure 2 – Part of the analyzed field. Well N is marked with a red oval, in which the pilot operation of directional radial drilling of 4 channels was carried out (well rate bubbles are combined with a reservoir pressure map)

Before simulating the location of radial channels in the reservoir, flow rate forecasts are performed to assess the results when drilling 2, 3, or 4 channels. Depending on the effective cost, and the resultant production performance the optimal number of channels to be drilled is selected.

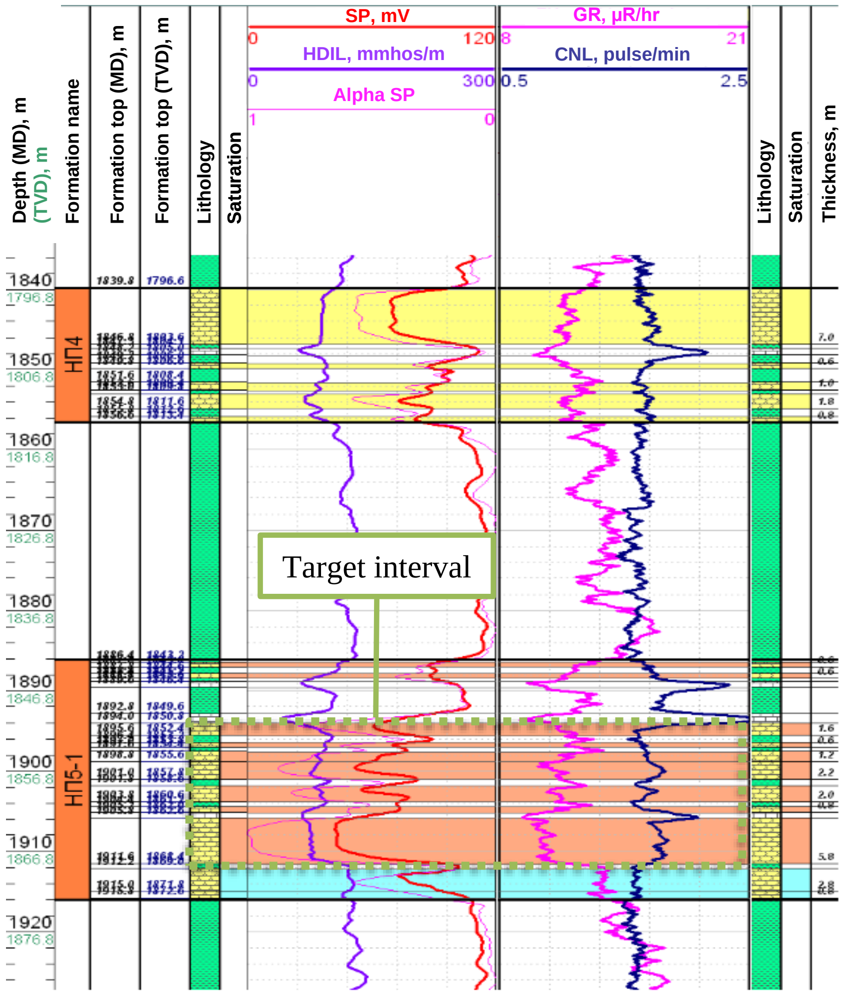
The following methodology was used to forecast flow rate:

• Based on well tests the contribution of the interval to the total flow rate estimated by the production logging data; the phase permeability of the tested intervals was estimated.

• Based on the permeability/porosity ratio of the tested intervals and the target intervals, the phase permeability of the target intervals was estimated;

• Based on the expected reservoir pressure, the drawdown was estimated and the expected skin factor after stimulation was used to calculate the predicted flow rates.

In addition, an analysis of net pay was performed based on the results of PLT (Fig.3). The analyzed reservoir operates most intensively in the interval 1886.4 - 1901.0 m, reservoirs in the interval 1901.9 - 1911.6 m operate much weaker, from the non-perforated part of the reservoir in the interval 1912.2 - 1915.0 m there is a weak flow of water to the lower perforations, there are also crossflows from above and from below.



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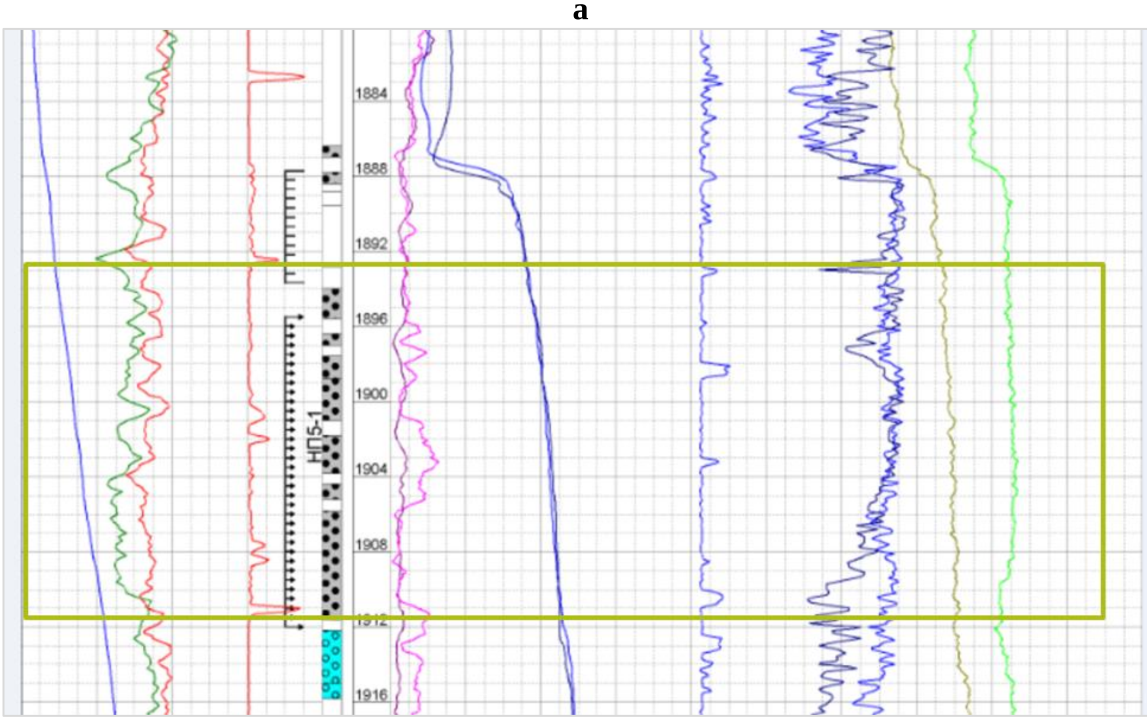

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Figure 3 – Open hole log plot (a) and PLT plot (b) for Well N

To estimate reservoir pressure parameters, skin factor and productivity index, the well test data was used.

The analysis was performed using the traditional technology of recording the build-up after the "Perfobore" job. The well was shut in. **Fig.4** shows a diagnostic LOG-LOG plot that allows you to estimate well and reservoir parameters.

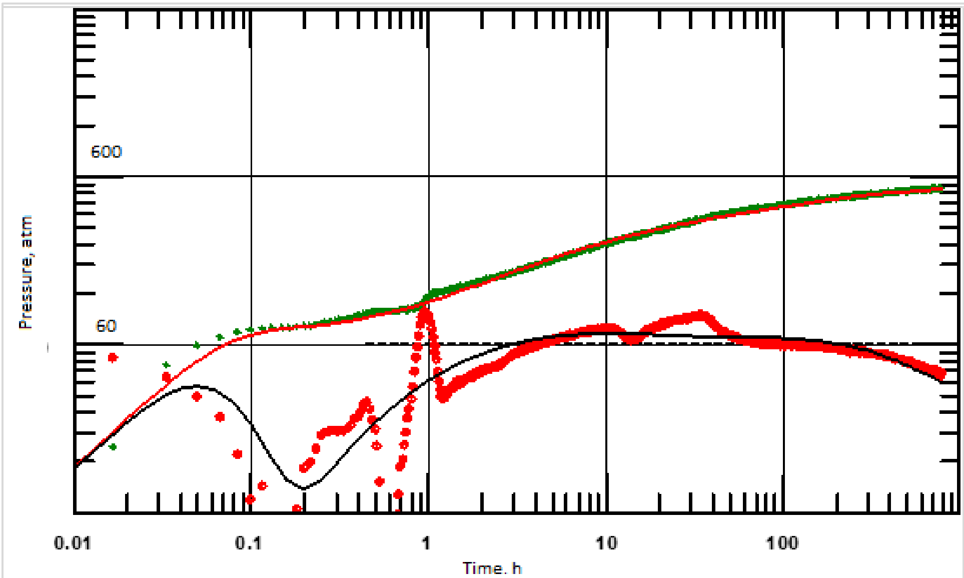


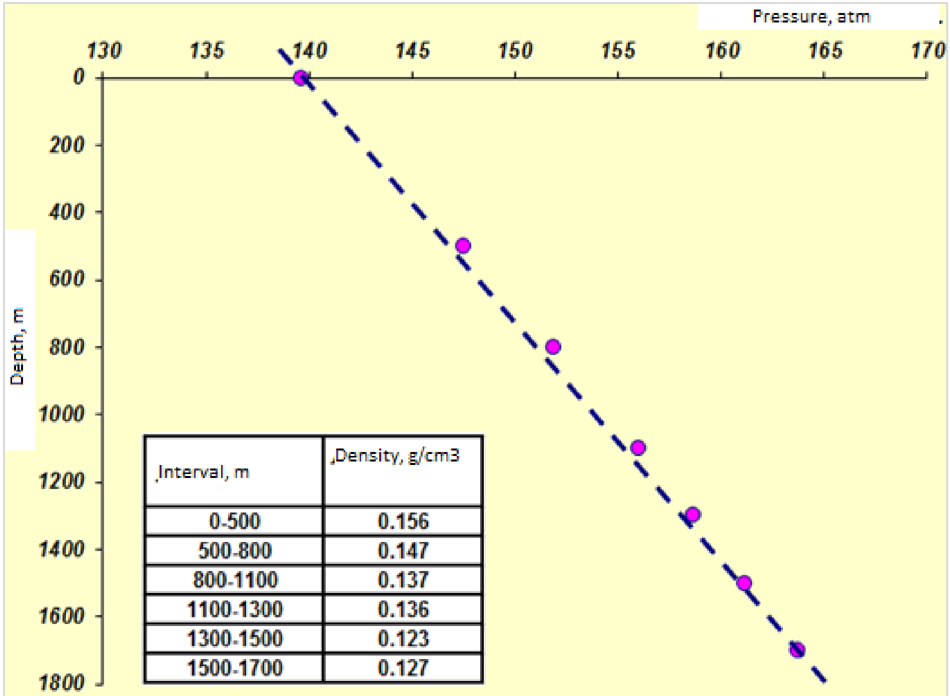
Figure 4 – Build-up's LOG-LOG graph (Well N)

At a later time, a drop in the pressure derivative is noted, which may be the result of the influence of the aquifer or injection wells. Table 1 shows the parameters obtained during the build-up interpretation.

Table 1 - Parameters obtained during PBU interpretation

Parameter	Value
Wellbore ratio	0.27
Transmissibility	13.7
Productivity index	1.35
Permeability	2.7 md
Skin-factor	-3.5
Estimated reservoir pressure (at the measurement depth of 1700 m)	168.3 atm
Bottom hole pressure (at the depth of measurement 1700 m)	79.4 atm
Distance to the sealing fault (L)	140 m

In addition, an analysis was carried out to estimate the pressure change profile in a shut-in well (after build-up). The diagram is presented in **Fig.5**. The calculated fluid density values are shown in the table on the graph.



Interval, m	Density, g/cm3
0-500	0.156
500-800	0.147
800-1100	0.137
1100-1300	0.136
1300-1500	0.123
1500-1700	0.127

Figure 5 – Pressure distribution in a shut-in well

Analyzing the graph, there are no obvious signs of fluid distribution changing. The shut-in wellbore is uniformly filled with fluid with an average density of 0.138 g/cm3.

The well production history was also analyzed (**Fig.6**). It can be seen that oil production is rapidly decreasing. Since 2015, oil production has decreased more than half. However, the production water cut increased sharply after hydraulic fracturing in 2015 and remains practically constant (25–33%).

Based on the results of the field data analysis, it was found that since October 2019, a significant redistribution of production across reservoirs has been made. In total, the well produces from two reservoirs. In 2019, production from one of them was increased by 1.5 times, and production from the other reservoir was reduced by 1.5 times.

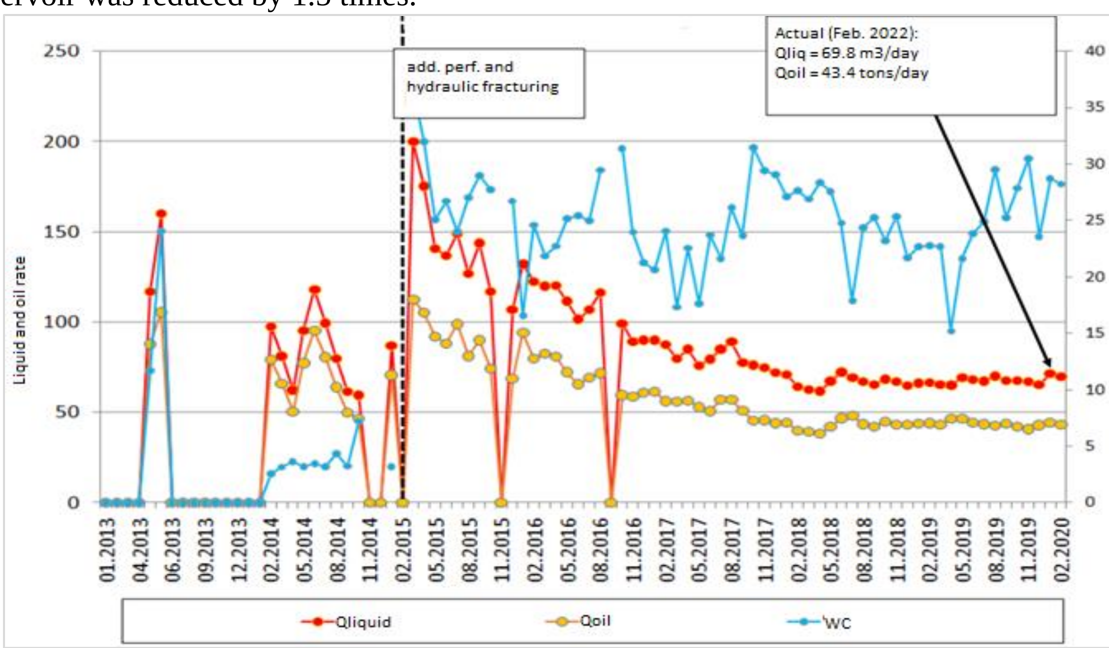


Figure 6 – Production history of Well N

It is believed that all water is produced due to poor quality cementing, or the destruction of cement and / or the formation of vertical fractures during hydraulic fracturing.

After analyzing all available field information, the predicted flow rate of the liquid is calculated using the Dupuis equation.

Fig.7 shows how the number of radial channels can influence the liquid rate increase. It is noted that under the conditions of the analyzed well, it is possible to increase the fluid inflow up to 30 tons/day.

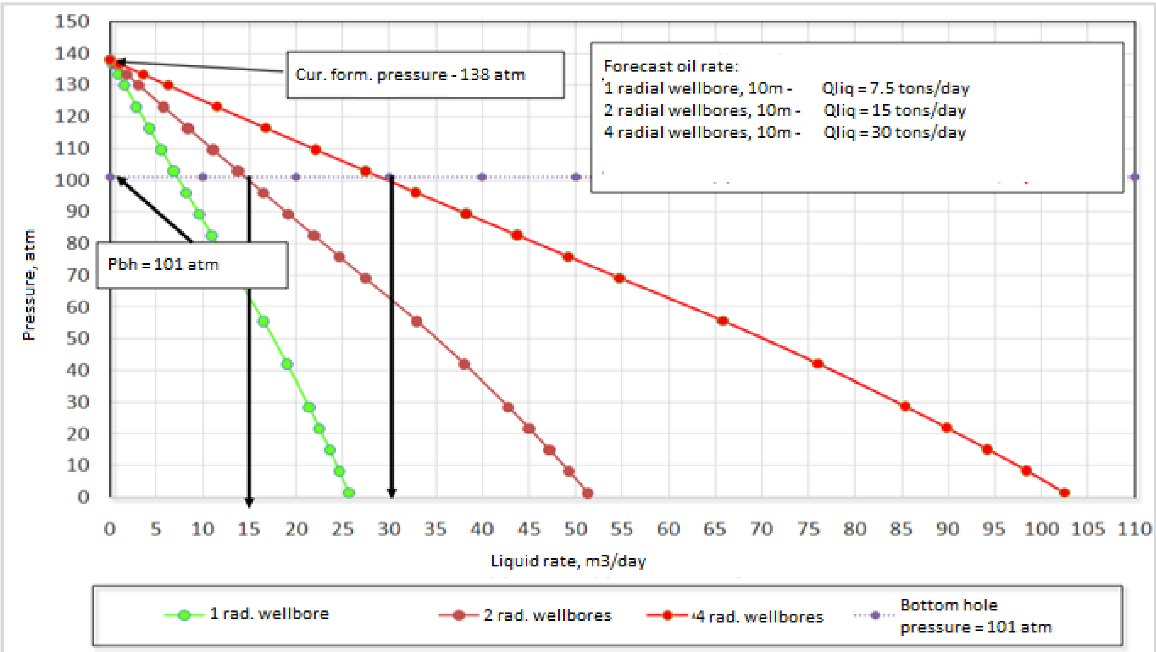


Figure 7 – IPR plot. Liquid rate increase Vs the number of radial channels

After the cost-benefit was evaluated, it was decided to drill 4 radial channels.

A retrievable anchor was installed by successive RIH & POOH operations. The first radial channel was drilled (window cutting – radial channel drilling - directional survey - liner installation inside the channel), the next three radial channels were similarly drilled and the anchor was removed. The liner is shown prior to installation in Fig 8 below.

It is worth noting that special liners have 0.5 mm mesh size and prevent sanding and shedding of drilled radial channels.

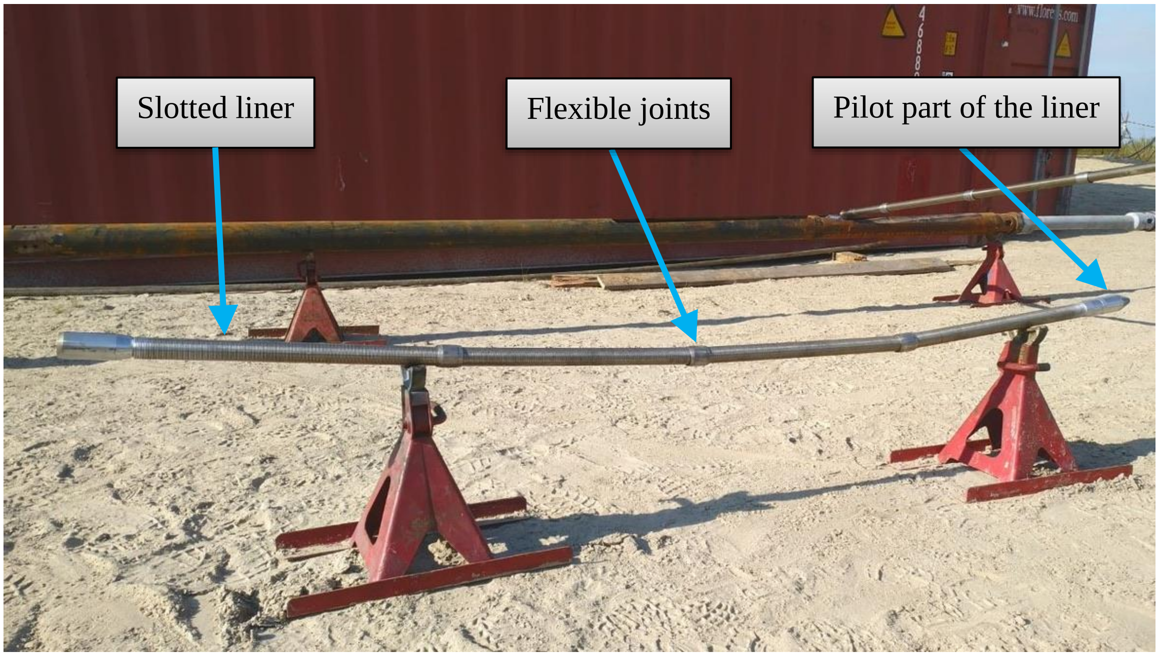


Figure 8 – Photo of the section of the "Perfobore" special liner before its installation inside the drilled radial channel

The deviations of the planned and actual trajectories were excellent at less than 40 cm (easily meeting the 10% target criteria).

Comparison of the actual and planned trajectories is shown in **Fig.9**.

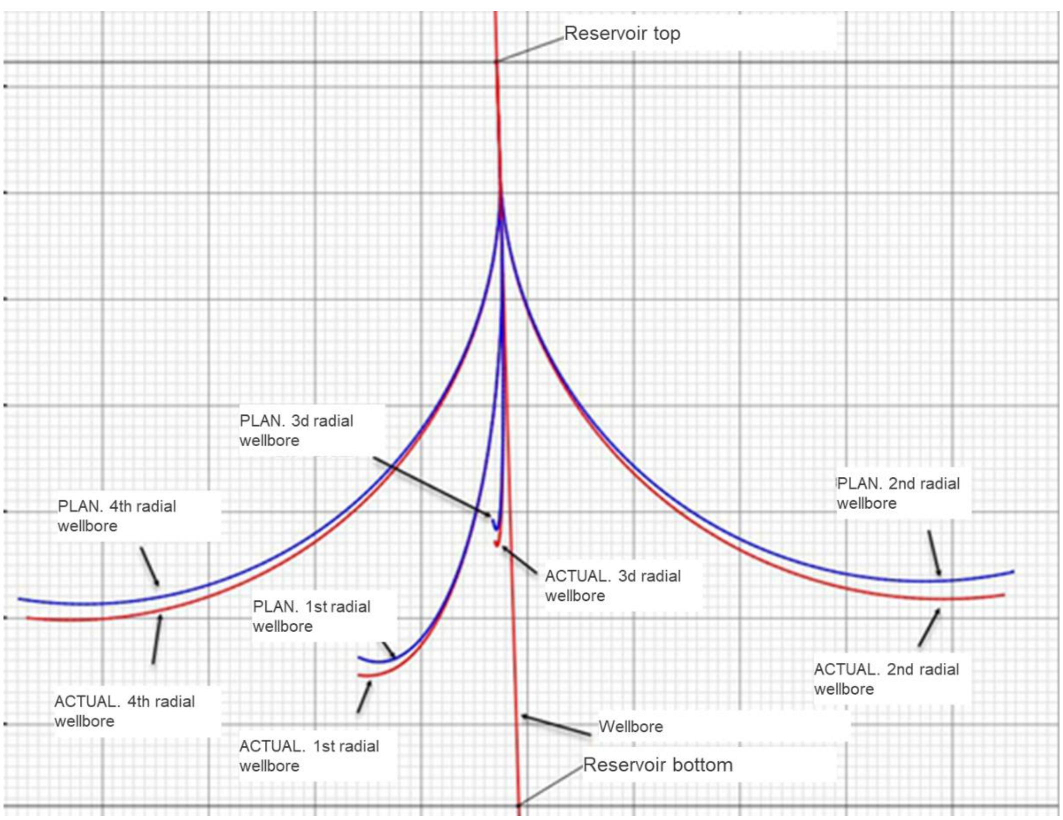


Figure 9 – Comparison of the actual and planned trajectories in the Well N (1 cell is 1 meter)

The drilling of radial channels in the analyzed field was performed in one more well which had been shut in for a long time due to high water cut. Well M has a horizontal completion. **Fig.10** shows the section of the field where Well M is located.

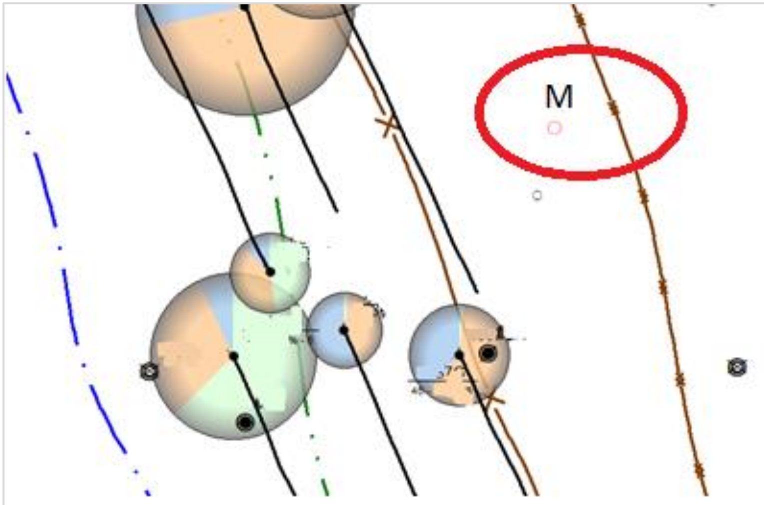


Figure 10 – Part of the analyzed field. Well M is marked with a red oval, in which pilot operations was carried out

The results of drilling 4 radial channels in Well M after production was started in 2020 (**Fig.11**) also showed excellent results. Within a month after drilling the radial channels the well reached a stable well operation. In a constant well operation, the increase in oil production was 41 tons/day and according to the PLT data, the main inflow (75%) is from the radial channels (**Fig.12**).

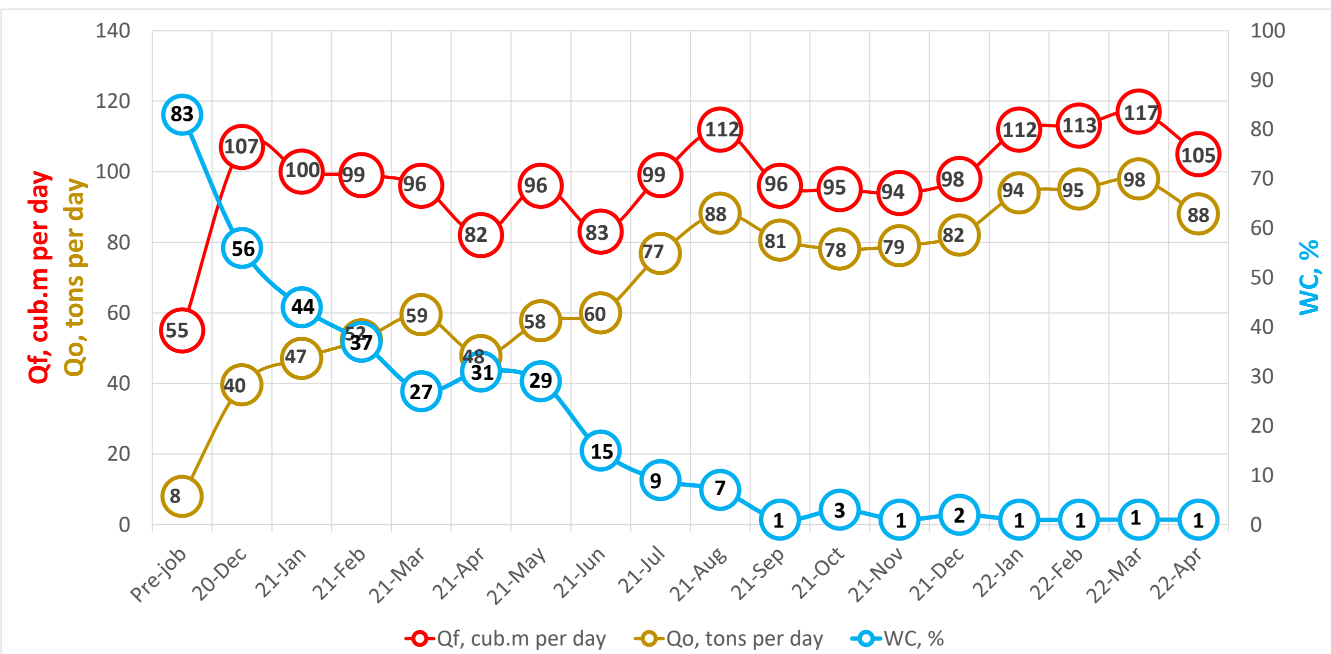


Figure 11 – Well M history after directional radial drilling

After drilling 4 radial channels in Well M, the PLT was carried out, which made it possible to evaluate the effectiveness of its production (**Fig.12**).

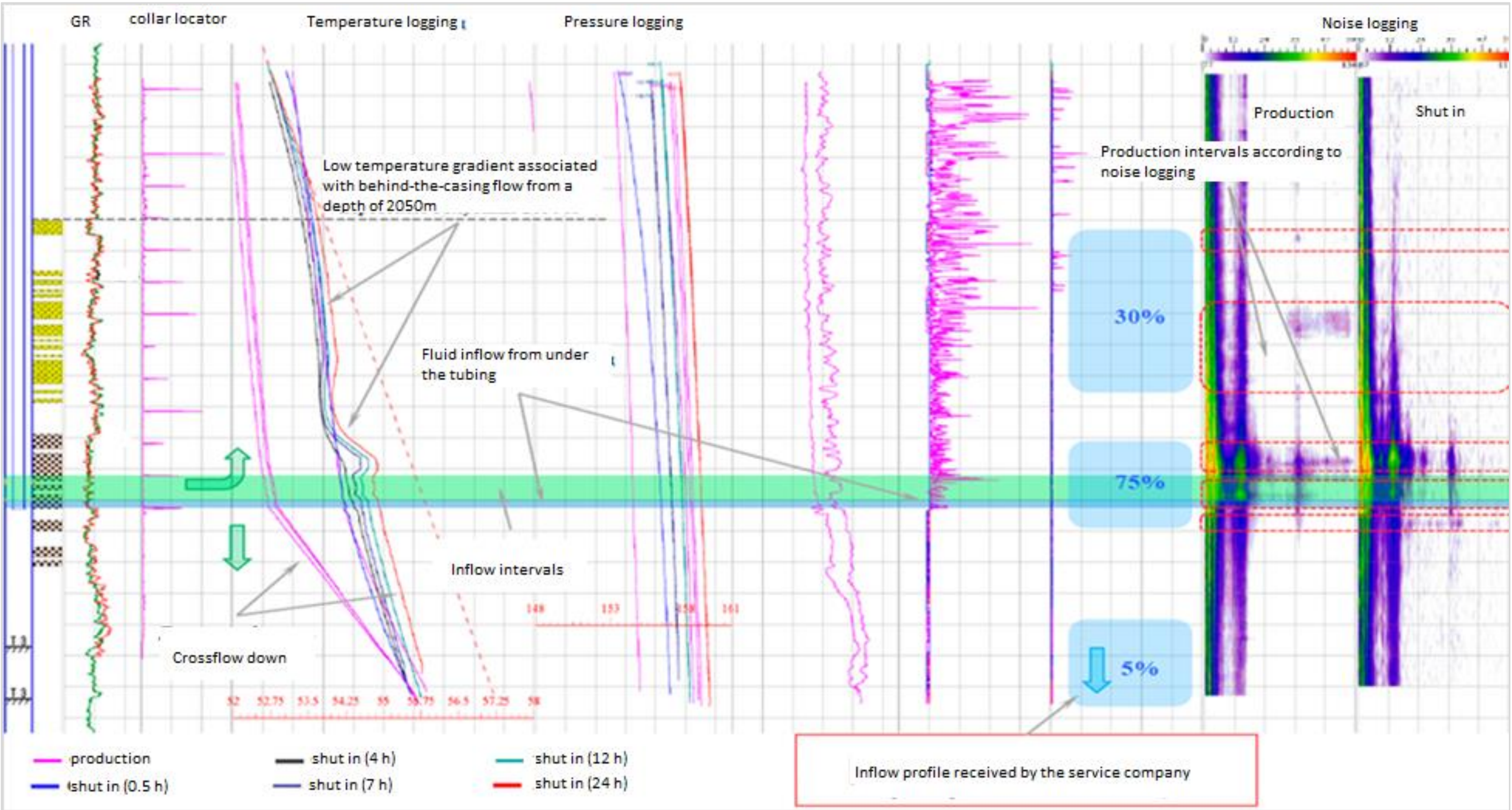


Figure 12 – PLT plot after radial drilling (Well M)

According to the PLT results, the main flowrate of 75% is observed from radial channels drilled using the Directional Radial Drilling technology, which strongly supports the effectiveness of the technology.

It should be noted that radial channels cannot be the cause of behind the casing crossflow, since the radial channels were drilled from a depth lower than the behind the casing crossflow.

Comparison of directional radial drilling and conventional perforation

Both directional radial drilling and conventional perforation are tools for increasing the “equivalent radius” of the well.

The Hawkins formula shows how the skin factor is affected by the permeability and radius of the near well bore zone during radial drilling or jet perforation.

$$s_d = \left(\frac{k_r}{k_d} - 1 \right) \ln \left(\frac{r_d}{r_w} \right)$$

where, k_r – reservoir permeability, k_d – near wellbore zone permeability, r_d – near wellbore zone radius, r_w – well radius [4].

Fig.13 shows a scheme of the well-reservoir system. The efficiency of applying one or another measure to increase the " equivalent radius" of the well will be higher if the technology allows expanding the well drainage area into the undamaged part of the formation.

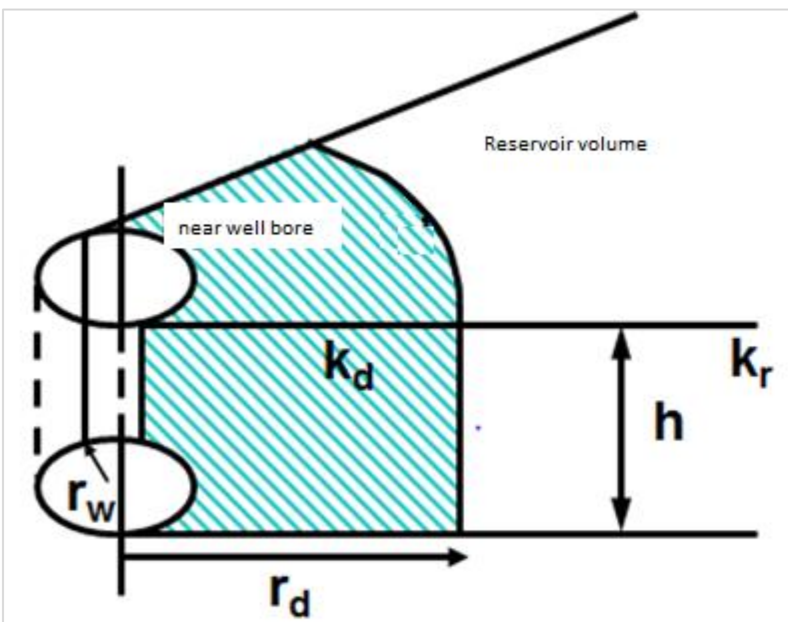


Figure 13 – Scheme of the "well-reservoir" system

Often, reservoir damage is formed in the near wellbore zone due to infiltration of drilling fluids or water, oil, gas, cementing and so on. The reservoir damage can reach several meters (see **Fig. 14**), which makes it impossible to overcome it by known methods of well completion and stimulation.
Therefore, in order to penetrate into the reservoir, technologies like directional radial drilling are needed that allow creating contact between the reservoir and the well over long distances.

Figure 14 – Scheme of the radial drilling

Table 2 summarizes the specifications of the Directional Radial Drilling technology and average specifications for 5 conventional perforators. The table shows that the penetration depth for all perforators does not exceed 2 m, which may be inefficient in conditions of wide reservoir damage.

Table 2 - Technical characteristics of jet perforators and Perfobore technology

Name of device / technology	Depth of penetration from the wellbore, m	Wellbore length, m	Diameter, mm
Average perforations (Compared 5 perforations)	1,33	1,33	11.86
DRD «Directional Radial Drilling»	**9,5**	**14**	**69**

Conclusions

Directional radial drilling is much more effective than conventional perforation.

The efficiency and effectiveness of the Directional Radial Drilling technology is confirmed in terrigenous reservoirs.

In order to confirm the technological applicability of directional radial drilling, field tests of the technology were carried out in two wells, the study were carried out in two stages:

• Confirmation of the possibility of accurately drilling radial channels directionally as planned (deviation of the actual channel from the design one by no more than 10%) in vertical Well N;

• Confirmation of the possibility of accurately drilling radial channels directionally as planned (deviation of the actual channel from the design one by no more than 10%) in horizontal Well M.

The test effectiveness criteria were:

• Possibility of drilling radial channels in vertical and horizontal wells. This criterion is met. Radial channels were drilled in a vertical well without complications.

• Deviation of the actual channel from the design one by no more than 10%. This criterion was partially fulfilled, for a vertical well the deviation was less than 10%, for a horizontal well the deviation was more than 10%.

A significant increase in production was obtained based on the results of the radial drilling.

Recommendations

Recommend the use of Directional Radial Drilling technology in wells that consist of small net pay, taking into account improvements based on the results of pilot tests of the non-standard perforation (radial completion) technology vs conventional perforation technology.

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