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Research of Operational Dynamics of a Well with Two Hydraulic Fractures with Use of Marked Proppant Penetrating into One Productive Formation

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Abstract

Use of a marked proppant during hydraulic fracturing allows for evaluation of the well operation during several years without extra expenses. The Paper describes the experience of placement of a polymer-coated marked proppant with different signatures for two hydraulic fracturing operations, penetrating into the top and the bottom of the productive formation by a vertical well. Hydraulic fracturing operation was performed in such a way that the hydraulic fractures made a single fracture, where two signatures of a marked proppant were placed.

Introduction

The article dwells on a new approach to the study of fluid flow distribution in directional wells with two hydraulic fractures. It discusses the results of using a technology that underwent integrated field tests in 2020–2021 in nine directional oil wells subjected to 2-stage hydraulic fracturing. The paper focuses on an explicit demonstration of production profile trends identified using the dynamic production profiling surveillance technology as well as the results of their comparison with conventional production logging.

Using the production profiling surveillance technology for studying wells treated with multi-stage hydraulic fracturing

One of the methods for deriving qualitative and quantitative data for each productive interval of horizontal and directional wells without downhole operations is the production profiling surveillance technology [1].

The marker-based technology designed for conducting studies in horizontal wells involves placing high-precision reservoir fluid flow indicators embedded in a polymer coating of proppant in hydraulic fractures. Such flow indicators are fluid phase sensitive and have affinity to specific phase only, making it easy to distinguish between indicators for water, gas or liquid hydrocarbon phases. Once the multi-stage hydraulic fracturing field operation is completed and a well is put into operation, reservoir fluid samples are taken from the wellhead and analyzed in a laboratory to identify the quantitative distribution of markers of each code resulting in quantitative data for each fluid phase of each individual fracturing stage. The process

of marking a multi-stage hydraulic fracturing-treated horizontal well and conducting production profile surveillance is shown in Figure 1.

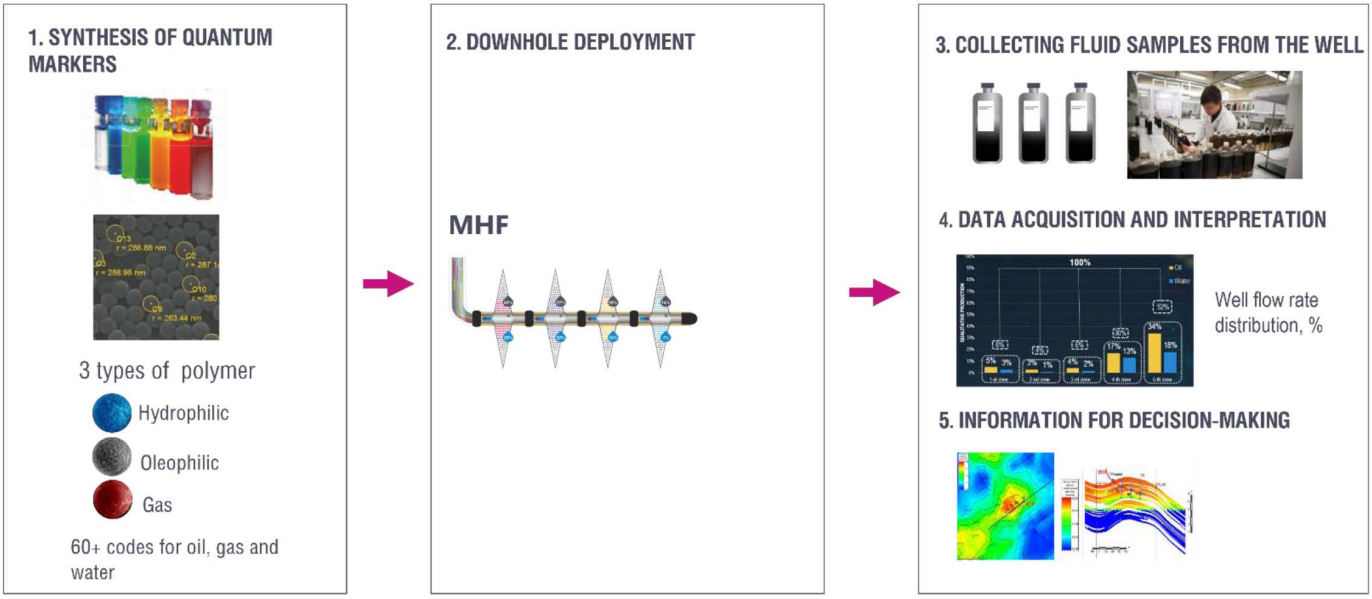


Figure 1—The process of marking and subsequent studies of a horizontal well using marked proppant

A marked proppant with marker-reporters embedded into its polymer matrix is injected into each multi-stage hydraulic fracturing stage (Figure 2).

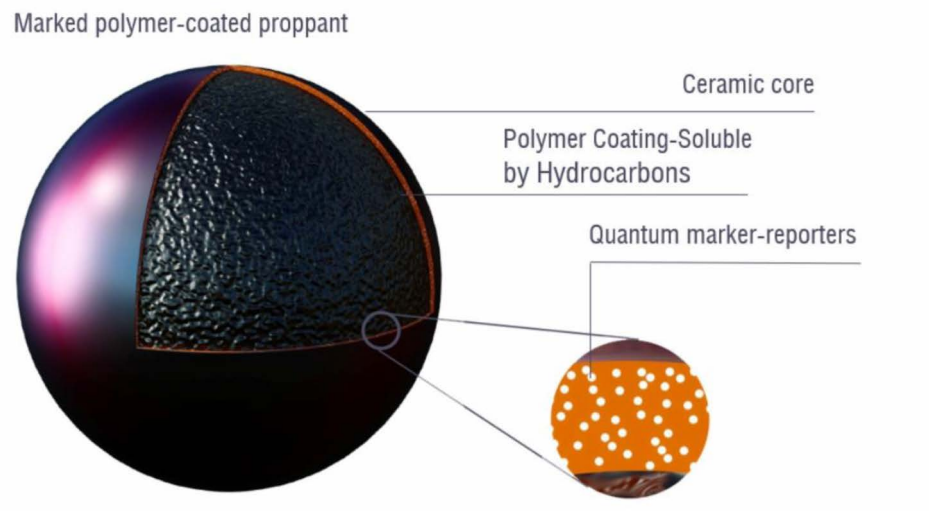


Figure 2—A grain of the marked polymer-covered proppant

Marker-reporters are polymer monodisperse microspheres doped with semiconductor nanocrystals with pronounced fluorescence properties (Figure 3) that are utilized for creating a marker code signature.

a) b)

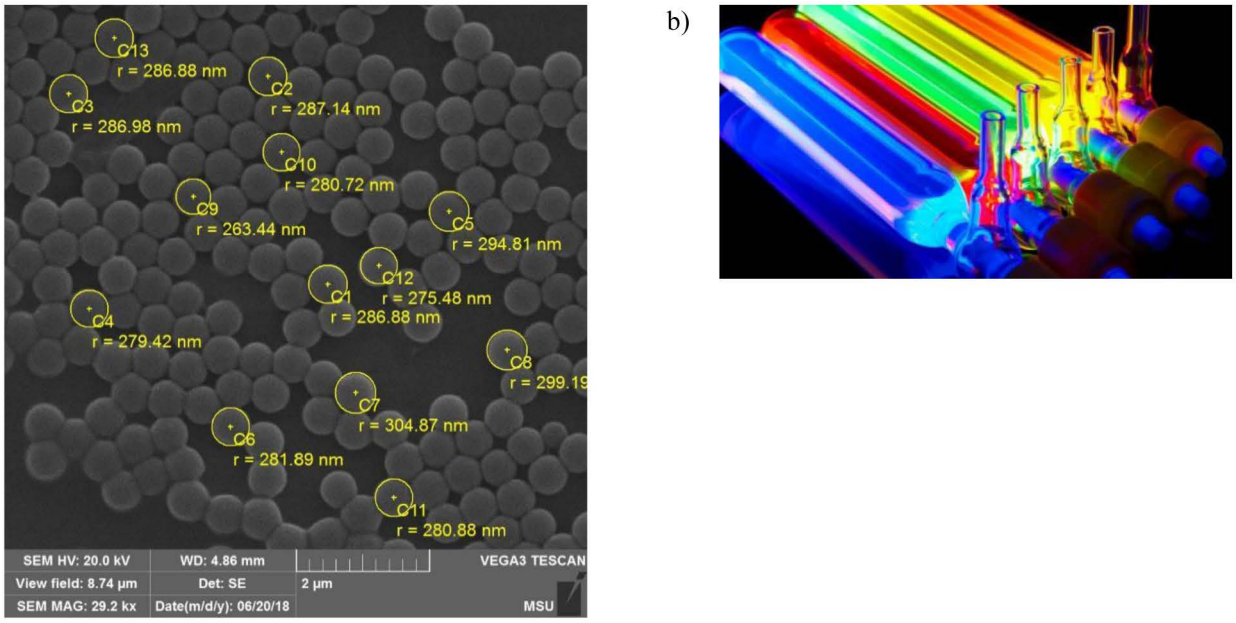


Figure 3—Quantum dot markers:a – photo in a scanning electron microscope;b – fluorescence of dispersions containing quantum dots

The marked proppant may have three types of polymer cover: gas or GF (designed for absorbing free gas), oleophilic or OF (designed for absorbing liquid condensate or oil), and hydrophilic or HF (designed for absorbing water). Figure 4 shows oleophilic and hydrophilic types of a proppant cover. Due to specific wetting properties, a cover is completely selective for each of the reservoir fluid phases and will stay dormant unless it comes into contact with the relevant fluid phase.

Figure 4—Water wettability of oleophilic (on the left — zero) and hydrophilic (on the right —complete) cover of marked proppant

Figure 5 shows the illustrative structure of the polymer cover of the marked proppant. Its main components are a solid insoluble polymer mesh that helps maintain the frame and is responsible for the strength characteristics of the cover. The matrix's "frame" houses a functional polymer filler, in which the marker-reporters are dispersed. The main function of the filler, once it gets in contact with a relevant reservoir fluid phase, consists in swelling and forming diffusion channels that serve as ways enabling the evacuation of marker-reporters from the inner layer of the polymer cover to the surface contacting the fluid, followed by their adsorption in the near-surface layer. If a fluid flows through a pack of marked proppant,

the mechanical energy of the flow is greater than the adsorption forces, so the markers are flushed from the polymer surface and carried by the target fluid phase.

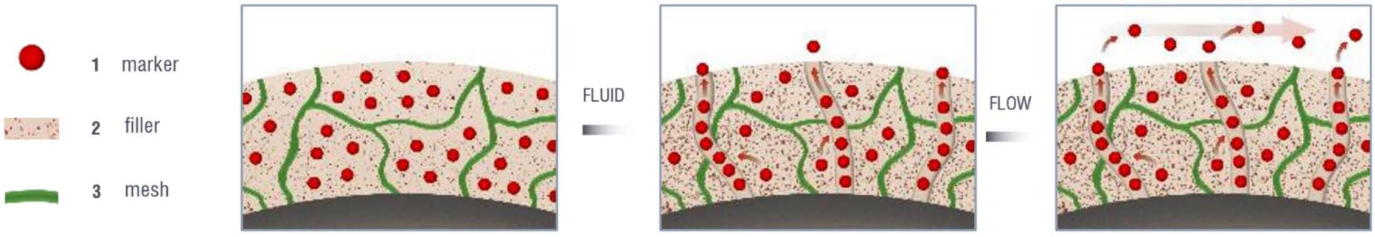


Figure 5—The principle of operation of the proppant's marker cover

After completing the field operation aimed at placing the marked proppant in the reservoir and once the well is put into operation, the next stage of production profiling studies includes taking reservoir fluid samples from the wellhead. Sampling can be done at any stage of the well production from flow back clean-up to steady stage. Subsequently samples are analyzed using the cytometry analytical system underlain by machine learning algorithms. This method involves a particle-by-particle analysis of dispersed media using light scattering signals. It helps identify the quantitative distribution of all types of markers of each code with high accuracy (Figure 6).

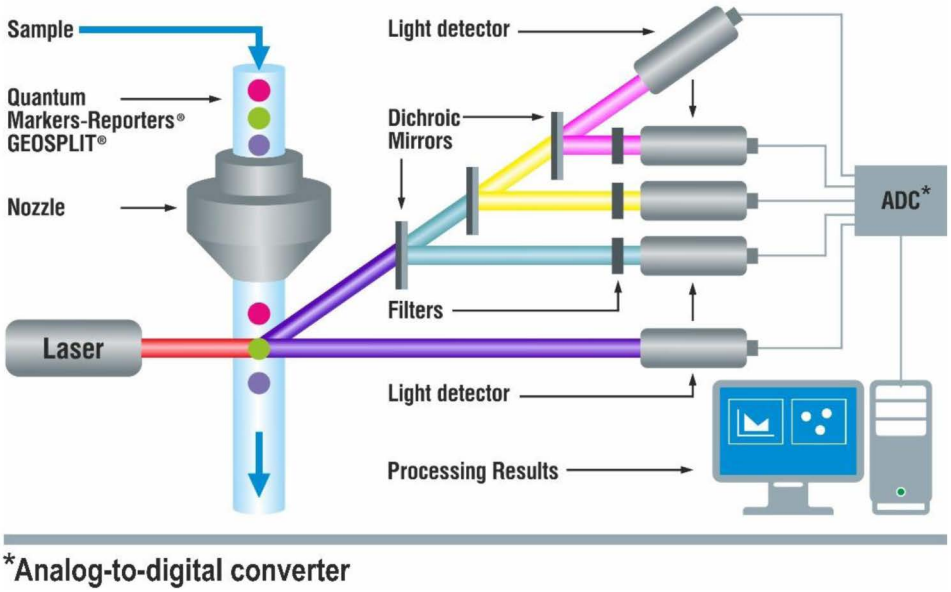


Figure 6—The analytical machine-learning-based system designed for quantitative identification of markers in fluid samples

A fluid string with a diameter of several microns is formed in the system's hardware and all markers line up strictly one after the other. This fluid string is then irradiated by a laser and, depending on a light scattering signal, markers of each code are identified. Thus, the analysis of the concentration of each marker code enables identifying the percentage of phases (hydrocarbon fluid, water, and free gas) in the total well flow rate.

The process of marker identification is fully automated and utilises machine learning algorithms, which makes marker identification highly accurate and efficient.

Field objectives addressed

The relevant objectives of studying horizontal wells subjected to multi-stage hydraulic fracturing using the marked proppant technology can include the following:

- Quantitative analysis of the inflow profile and composition by frac ports;
- Quantitative analysis of the inflow distribution between the near and far hydraulic fracturing zones;
- Monitoring of water breakthrough intervals;
- Assessment of the reserve recovery in a reservoir zone along the horizontal well.

In the course of continuous production and geophysical monitoring of production and development for a number of fields, significant data arrays have been accumulated, on the basis of which the factors that determine the "nature" of horizontal well inflow profiles have been systematized [6]:

- Design and engineering factors that are related to wellbore orientation and drilling, hydraulic fracturing design, etc., in other words these are the factors that were laid down and implemented during the construction of the well and the stimulation of production;
- Geological factors, which include the heterogeneity of the porosity and other reservoir properties, its structure and other geological characteristics;
- Hydrodynamic factors that are associated with the processes of downhole hydraulics and underground hydrodynamics in the implementation of the field development system;
- Clogging is a separate group of factors associated with mechanical clogging of the wellbore and bottomhole formation zone.

The technology offers such key effects as:

- Optimizing multistage hydraulic fracturing.
- Optimizing design solutions (orientation of horizontal wellbores and hydraulic fractures relative to regional stress, distance between ports)
- Better quality of ongoing field monitoring and control over horizontal well production parameters, inter alia, achieving the rational reserves recovery along the wellbore, preventing premature flooding of frac ports and enhancing their performance.

Conducting integrated field tests

Currently, considerable experience has been accumulated in conducting integrated laboratory and bench tests of the dynamic marker-based production profiling surveillance technology, including the accuracy of quantum marker-reporter calculation as well as identification of their physical, chemical and thermal stability, etc. [4]. The very dynamic marker-based production profiling surveillance method has been recognized as an innovative industry standard for field monitoring and control over production and development.

The purpose of this study was to conduct integrated field tests of the technology in 9 directional wells using marked proppant. Well surveys were conducted in 2020—2021 [5].

Two-stage hydraulic fracturing was performed in all wells. Well data is given in Table 1. On average, 2.6 tons of proppant were used per linear meter of perforation.

Table 1—Information on hydraulic fracturing in the directional wells in question with two hydraulic fractures [5]

Well no.	Formation	Perforation interval, m		Total perforation, m	Total quantity of proppant, t	Total quantity of proppant per 1 linear meter of perforation, t/m
1	Ach_3	2,700	2,719	19	40	2.1
	Ach_2	2,669	2,689	20	40	2.0
2	Ach_3	2,897	2,910	13	30	2.3
	Ach_2	2,844	2,881	37	50	1.4
3	Ach_3	2,887	2,895	8	30	3.8
	Ach_2	2,841	2,863	22	50	2.3
4	Ach_3	2,984	3,008	24	40	1.7
	Ach_2	2,958	2,970	12	40	3.3
5	BV_8–bottom	3,269	3,277	8	45	5.6
	BV_8–upper	3,239	3,259	20	15	0.8
6	BV_8–bottom	3,032	3,042	10	27	2.7
	BV_8–upper	3,008	3,013	5	8	1.6
7	BV_8–bottom	2,978	2,984	6	25	4.2
	BV_8–upper	2,950	2,957	7	25	3.6
8	T_2	2,405	2,410	5	20	4.0
	T_1	2,379	2,392	13	20	1.5
9	$YuSh_4$	2,657	2,676	19	40	2.1
	$YuSh_2$	2,616	2,638	22	40	1.8

The studies were performed on layers Ach $_1$-Ach $_3$, BV $_8$ (lower and upper sedimentation pattern), T $_1$-T $_2$, and YuSh $_2$-YuSh $_4$ of a Western Siberian deposit group.

The Achimov group formations (Figure 7) are characterized by a highly compartmentalised structure with alternating water- and oil-saturated interlayers and low permeability up to 4 mD.

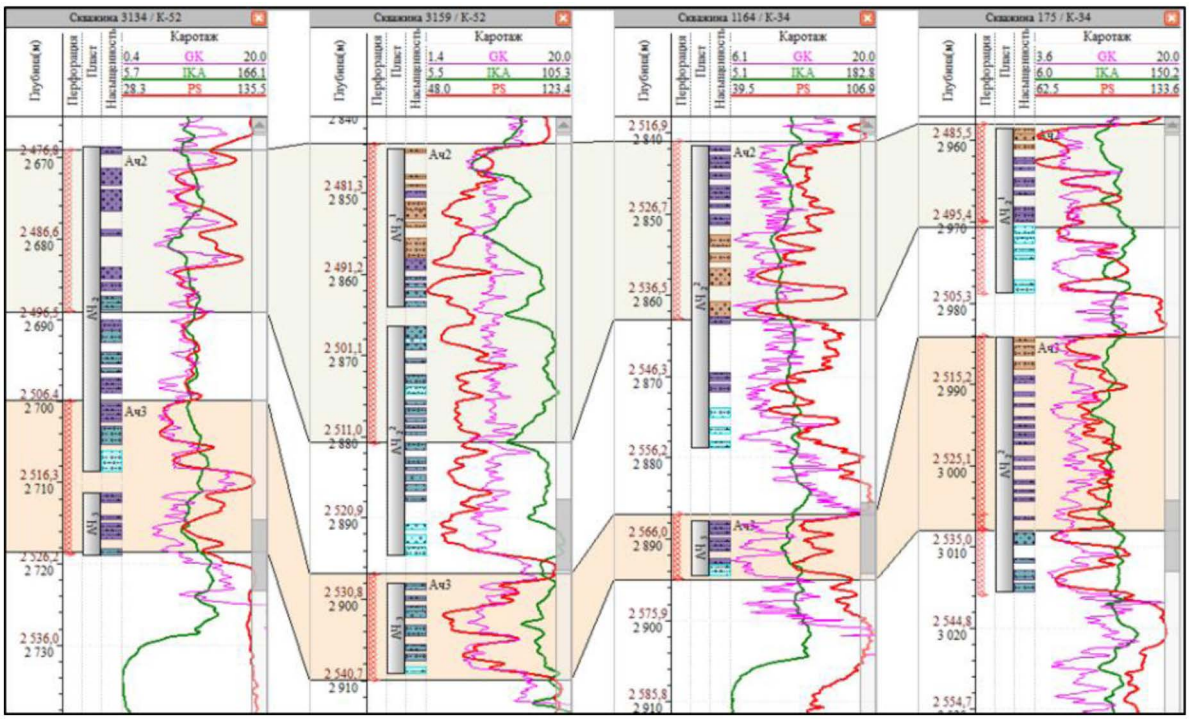


Figure 7—Log correlation for formations Ac $_2$ and Ac $_3$ of Potochnoye field [5]

Another productive formation BV $_8$, on which marker studies were also performed, features two sedimentation patterns separated by a clay bridge with a thickness of 10 to 20 m (Figure 8). The permeability of individual interlayers can reach several dozens of mD.

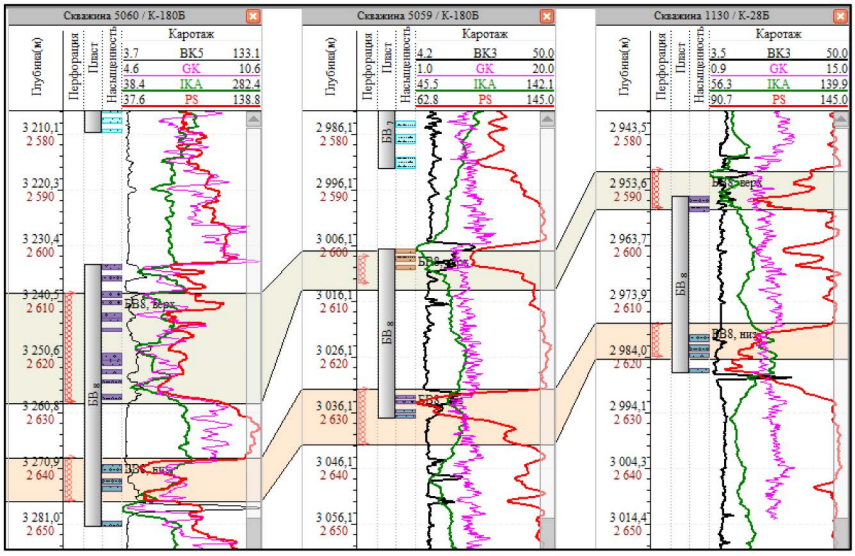


Figure 8—Log correlation for formations BV $_8$ (lower and upper sedimentation patterns) [5]

Reservoirs in formations T $_1$–T $_2$ and YuSh $_2$–YuSh $_4$ are characterized by thin oil-saturated net pays and low density of current mobile reserves. According to logs for wells Nos. 3171 and 9844 (Figure 9), individual productive deposits are represented by highly compartmentalised sandstones with high clay content.

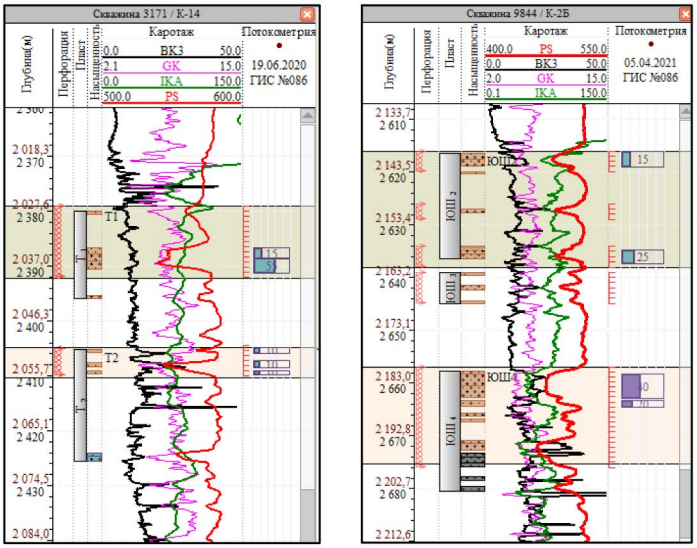
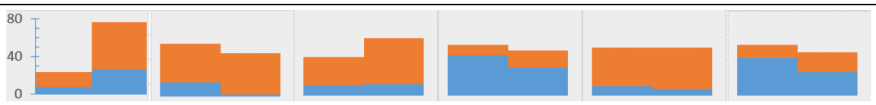
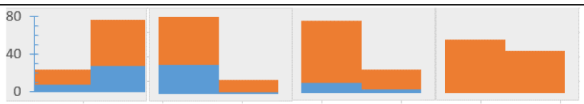
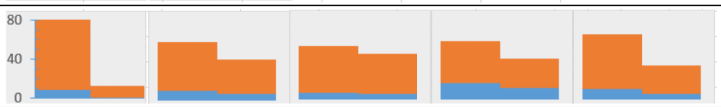
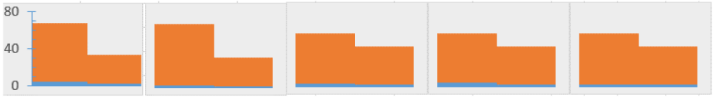
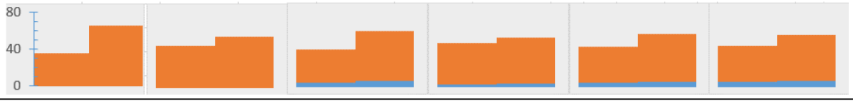
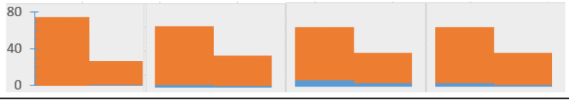


Figure 9—Logging along geological sections of T $_1$—T $_2$ and YuSh $_2$—YuSh $_4$ [5]

Dynamic marked-based production profiling surveillance was performed on each well during one year or longer, which yielded a dynamic picture of the profiles of fluid coming from the formations (Table 2).

Table 2—Summary data of dynamic marked-based production profiling surveillance conducted in directional wells [5]

well no.	Formation	Production profiling surveillance period	Inflow distribution by month (lower interval on the left, upper interval on the right)
1	Ach_3 Ach_2	08.2019—06.2020	
2	Ach_3 Ach_2	01.2020—12.2020	
3	Ach_3 Ach_2	01.2020—06.2020	
4	Ach_3 Ach_2	10.2019–06.2020	
5	BV_{8}–lower BV_{8}–upper	01.2021–06.2021	
6	BV_{8}–lower BV_{8}–upper	12.2020–04.2021	
7	BV_{8}–lower BV_{8}–upper	06.2020–10.2020	
8	T_2 T_1	07.2020–12.2020	
9	$YuSh_4$ $YuSh_2$	04.2021—08.2021	

The production profiling surveillance effort showed the following:

- for three wells (No. 1, 5, and 8), the fluid flow from the upper interval turned out to be heavier than that from the lower interval during almost the entire surveillance cycle;
- for four wells (No. 2, 4, 7, and 9), a smoother fluid flow profile is seen with a trend to increasing inflow from the upper interval;
- for well No. 1, increase in the well production water-cut from 66% in August 2019 to 97% in June 2020 was observed, which occurred due to a water breakthrough from the overlying interval.

In general, for all wells, the inflow from the lower intervals (53.4%) was quite comparable to the inflow from the upper intervals (46.6%), which proves the effectiveness of the field development strategy chosen and multi-stage hydraulic fracturing. In addition, the overall divergence in the performance of the upper and lower intervals did not reach critical values – the minimum performance observed was 33% for the upper layer of well No. 9 and, respectively, the maximum performance was 67% for the lower interval.

Conventional logging in the form of downhole flow measurements was performed in four wells before commissioning. The average divergence between the data yielded by dynamic marker-based production

profiling surveillance and conventional logging was 4.3%, which is evidence of high efficiency. The divergence obtained is most likely the result of the lower sensitivity of the flow measurement method (for a number of wells, the sensitivity accuracy of the conventional logging method was ± 10%), while the discreteness of the marker-reporter identification does not exceed ± 0.1%. In addition, for well No. 5, due to the little inflow in the gas lift process (fluid flow rate below 1 m3/day), the flow meter data turned out to be below the sensitivity threshold, so it was impossible to measure the inflow distribution using conventional logging.

If we compare the results of marker-based studies with the data derived by means of downhole flow measurements with a single turbine (Table 3), it can be concluded that the advantage of dynamic marker-based production profiling surveillance technology is the possibility of reliable operation regardless of the well drive and fluid flow profile.

Table 3—Comparison of fluid flow from the upper and lower formation intervals [5]

well no.	Formation	Fluid flow distribution obtained using marker-based technology, %	Fluid flow distribution obtained using conventional logging (flow measurements), %	Divergence, %
1	Ach_3	36.5	No conventional logging was performed	-
	Ach_2	63.5		
2	Ach_3	46.0	No conventional logging was performed	-
	Ach_2	54.0		
3	Ach_3	60.0	No conventional logging was performed	-
	Ach_2	40.0		
4	Ach_3	65.0	No conventional logging was performed	-
	Ach_2	35.0		
5	BV $_{8}$–lower	36.2	100	-
	BV $_{8}$–upper	63.8	Undetectable	
6	BV $_{8}$–lower	66.4	No conventional logging was performed	-
	BV $_{8}$–upper	33.6		
7	BV $_{8}$–lower	61.2	62	**0.8**
	BV $_{8}$–upper	38.8	38	
8	T_2	35.0	30	**5.0**
	T_1	65.0	70	
9	YuSh $_4$	67.0	60	**7.0**
	YuSh $_2$	33.0	40	
Average deviation, %				**4.3**

In order to summarise the results, a dimensionless integrated criterion was introduced to reflect the effect of 6 geological, physical and technological factors potentially affecting the production profile:

- Total quantity of proppant;
- Perforation length;
- Oil-saturated net pay;
- Permeability coefficient;
- Compartmentalization coefficient;
- Net-to-gross ratio.

This approach involves individual assessment of the selected parameters for each productive formation, where a certain weight is assigned to each factor. Value 0 means that a specific characteristic has approximately the same value. Values modulo 1 or higher are assigned in case of divergence – the larger the value, the more significant the divergence. Next, an integrated parameter – the sum of variable terms – is calculated.

The analysis described above reveals a significant degree of convergence of the data and the identified trends (Table 4). In wells Nos. 3134, 5060, and 3171, with a positive integrated parameter, the fluid flow from the upper interval is higher than from the lower interval throughout the monitoring cycle. In other wells No. 3159 and 1164, also with a positive integrated parameter, the fluid flow from the lower interval was predominant at the beginning of observations, however, the contribution from the upper interval was increasing during the production from the well under study. In wells Nos. 175, 5059, and 1130, with a negative integrated parameter, the inflow from the lower interval is greater than from the upper interval.

Table 4—Comparison of geophysical and technological parameters of the wells under study [5]

Well	Formation	Total quantity of proppant, t	Perforation, m	Net oil pay, m	Permeability coefficient, mD	Compartmentalisation, unit	Net to gross, decimal fraction	Variables (for items 1–6)						Sum of variables (integrated parameter)
		1	2	3	4	5	6	1	2	3	4	5	6	
	Ach3	40	19	9	2.2	7	0.61							
1	Ach2	40	20	7.76	4.1	7	0.59	0	0	0	2	0	0	2
	Ach3	30	13	5.45	2.9	7	0.46							
2	Ach2	50	37	18	2	21	0.53	2	3	3	-1	-1	1	7
	Ach3	30	8	3.85	1.1	3	0.6							
3	Ach2	50	22	13.52	0.3	10	0.61	2	3	2	-1	-1	0	5
	Ach3	40	24	9.78	3.4	16	0.41							
4	Ach2	40	12	6.61	1.4	7	0.54	0	-2	-1	2	-1	1	-5
	BV8–lower	45	8	3.36	11.9	3	0.4							
5	BV8–upper	15	20	8.26	39	8	0.41	-2	3	2	3	1	0	7
	BV8–lower	27	10	2.2	100.1	4	0.21							
6	BV8–upper	8	5	1.6	9.5	2	0.29	-2	-2	0	5	0	1	-8
	BV8–lower	25	6	2.86	29.3	3	0.44							
7	BV8–upper	25	7	1.97	12.6	2	0.24	0	0	-1	2	0	2	-5
	T2	20	5	1.88	38.2	3	0.35							
8	T1	20	13	4	38.7	2	0.33	0	3	1	0	2	0	6
	YuSh4	40	19	9	2.4	6	0.61							
9	YuSh2	40	22	5.8	2.8	5	0.27	0	0	-1	0	-2	3	-6

Conclusions

1. The fluid flow profile data obtained using quantum marker-reporters enabled conducting a long-term analysis of the productive intervals of the directional wells under study.
2. The results of qualitative and quantitative analysis of the samples taken lead to reasonable conclusions concerning the performance of a well's productive intervals. A unique marker code is used for each productive interval, thereby eliminating the possibility of errors in data interpretation.
3. There is high convergence of the data obtained using the marker-reporters technology and the data derived by conventional logging tools.
4. The production profiling surveillance technology involving the use of marked proppant has a big potential for addressing vital objectives in field development. In particular, these are:

    - Determining the optimal quantity of proppant per stage and the optimal geometric parameters of a hydraulic fracture in terms of the length–height ratio.
    - Evaluating the interference between hydraulic fractures in order to identify the optimal distance between the frac ports.

- Identifying the optimal trajectory of a horizontal wellbore (azimuth angle, zenith (inclination) angle, tortuosity) and the orientation of hydraulic fractures relative to regional stress and studying the influence of these factors on the reserves recovery uniformity along the horizontal well in the long run.
- Studying the effects of the proximity of gas-oil and gas-water contact and other geological conditions on the performance of hydraulic fractures.
- Ongoing field monitoring and control over horizontal well production parameters, inter alia, to achieve the rational reserves recovery along the wellbore, prevent premature flooding of frac ports and enhance their performance.

References

1. Marker-based production logging and profiling surveillance for efficient field development management/ M. D. Dulkarnaev, K. N. Ovchinnikov, K. M. Saprykina, E. A. Malyavko. *Engineering Practice*, 2018, No. 11, pp. 40—47.
2. M.I. Kremenetsky, A.I. Ipatov *Using production logging tools to optimise oil and gas field development*. Volume **2**. The role of hydrodynamic and geophysical monitoring in field development management.—Moscow—Izhevsk: Institute of Computer Research, 2020. —756 p.
3. Guryanov A.V. Production Logging Using Quantum Dot Tracers. — *Coiled Tubing Times Journal*, 2017, No. 02, pp. 42–51.
4. Comprehensive Study of Tracer-Based Technologies in Reservoir Conditions/M. Dulkarnaev, K. Ovchinnikov, A. Guryanov, A. Anopov, E. Malyavko. SPE-192564-RU, a paper for the SPE Annual Caspian Technical Conference and Exhibition, October 31–November 2, 2018, Astana, Kazakhstan.
5. Using quantum marker-reporters for production profiling surveillance in directional wells with two hydraulic fractures / V.F. Pyzykov, E. A. Malyavko, O. A. Gorbokonenko. – *Oil. Gas. Innovations*, 2021, No. 9, pp. 94–99.
6. A. I. Ipatov, E. A. Malyavko. What happens to the inflow profiles of horizontal wells after development. – *Oil and gas vertical*, 2022, No. 6, p. 88–97.