SPE-196830-MS

Evolution of Horizontal Wells Production Logging Using Markers

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This paper was prepared for presentation at the SPE Russian Petroleum Technology Conference held in Moscow, Russia, 22 – 24 October 2019.

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Abstract

There has been an increased interest in horizontal wells production logging using markers due to objective difficulties not only in conducting geophysical production logging and data interpretation, but also because existing technologies provide bottom hole data only for a very short time period when the PLT complex is in the well. Marker technologies enable users to obtain data in a much larger volume and practically non-stop for several years without changing the well mode of operation. This in turn allows for analyzing the influence of many external factors on the horizontal well intervals operation.

This article presents the experience of marker technologies that were tested and implemented at Gazpromneft PJSC sites from 2016 to 2019, and is aimed at the systematization of objectives and requirements for the technology, as well as addressing important issues during the tendering procedures for the oil producing companies.

Introduction

Development of hard-to-recover reserves of the Bazhenov Formation is an urgent task due to the depletion of existing large fields. Currently, the total volume of production of these types of hydrocarbons from non-traditional collectors is about 1%, but it is experiencing steady growth of their development and the improved ability to compete with the projects for oil extraction from traditional reserves. According to analysts, by 2020–2025 the share of oil obtained using alternative sources will total about 5% of world oil production. In Russia, the priority for the development of unconventional hydrocarbon reserves is shale oil. The significant distribution of "domanicoids" and "bazhenites" in the area and in the main oil and gas reservoirs, as well as their abundance of industrial inflows, provides the opportunity for large-scale production of this oil reserves using modern technologies. According to some estimates, the prospective oil production from the Bazhenov formation in Russia will be 15–20 million tons by 2020 and will reach 70 million tons by 2030.

In the Bazhenov formation, the process of organic matter conversion into oil has not yet been completed. So the reservoir, in addition to light oil, contains hydrocarbons along with the formation-forming part — kerogen. A unique industrial value is high oil saturation. These high- quality hydrocarbons – light, low-sulfur, and without other harmful impurities – require no significant costs for primary and deep processing.

The history of the joint development of the Bazhenov-Abalak deposits of the Bazhenov formation located in Western Siberia proves that it differs from the development of traditional reservoirs. The following characteristics are noted:

– a variable area distribution of wells with high initial inflow rate
– a significant amplitude of the initial and subsequent flow rates, ranging from tons per day to several hundred tons per day
– anomalously high reservoir pressure, exceeding hydrostatic pressure by 60%, which indicates the presence of significant oil reserves that led to the formation of fractures and increase in pressure, and potentially high oil recovery rates in the volumetric expansion drive;
– a significant increase in well production after multi-stage hydraulic fracturing (MFrac);
– a sharp decline in well productivity: the flow rate may decrease considerably during the year.

With a significant volume of reserves, the key factor is reservoir permeability. Currently, the primary mechanism for ensuring the fluid flow into the Bazhenov formation wells is the oil filtration through a system of natural fractures. However, the real fracturing is weakly developed, and the permeability varies from 0.001 to 0.03 μm2. This is perhaps due to the lack of inflow in the wells with a clearly oil-saturated core.

Due to the above-mentioned technological objective to develop the Bazhenov formation, the creation of the secondary permeability of the oil-saturated matrix due to the dense system of induced fractures is crucial. This is ensured by the technology of horizontal wells drilling with multi-stage hydraulic fracturing. In this case, the main objective of hydraulic fracturing is to provide enhanced reservoir fracturing, and create secondary permeability in the drainage area of the well. Due to the technical difficulties of field geophysical production logging and the ambiguity of the results obtained in horizontal wells of fields with hard-to-recover reserves, the objective is obtaining new methods for evaluating hydraulic fracturing quality and horizontal well performance in addition to traditional fluid flow metering, temperature logging, water-cut and spectral noise logging and micro seismic logging (Ovchinnikov, Gurianov, Buzin, Katashov, Dubnov, Agishev, 2017).

Objectives for horizontal wells production logging using markers with multi-stage hydraulic fracturing

One of the tools that allow for obtaining detailed information from the well is production logging of wells using markers and high-tech materials. This approach serves to solve the problem of hard-to-recover reserves development with an increase in the amount and frequency of the information obtained from the horizontal well bottom, which can be used for:

- Analysis of the long-term dynamics of the production logging data interpretation results;
- Development of recommendations for improvement of well operation efficiency using multi-stage hydraulic fracturing (oil flow rate, water cut);
- Evaluation of hydrocarbon reserves production;
- Localization of residual mobile reserves;
- Recommendations for changing the well operation mode;
- Determination of the hydraulic fractures' dynamic characteristics;
- Additional tools for validation of micro seismic monitoring and geophysical research data;
- Analysis of the field geological structure and the available information on wells with multi-stage hydraulic fracturing;

- Actualization of the geological model, taking into account new wells with multi-stage hydraulic fracturing;
- Reproduction of the process for the development of the reserves in sectoral three-dimensional hydrodynamic models, considering the operating data of each interval;
- Evaluation of the feasibility of compaction drilling based on dynamic well tests.

Production logging method using markers with the application of proppant marked with quantum dots

Conducting production logging of hydraulic fracturing stages with marked proppant leads to an increased amount of data over time while decreasing the necessary resources and improving safety. An important part of the tracer-based technology is the synthesis of marker-reporter combinations of quantum dots stabilized with a polymer shell. Quantum dots are nanocrystals that are 1-2 nanometers in size, obtained by colloidal synthesis and coated with a layer of adsorbed surface-active molecules. Quantum dots are obtained through a method of colloidal synthesis based on cadmium chalcogenides that fluoresce in different areas of the electromagnetic spectrum, depending on their size (RF patent №2018126690, 20.07.2018). Marker-reporters created from quantum dots have the unique ability to absorb energy in a wide range of the spectrum and emit a narrow spectrum of light waves, which can be recorded using flow cytometry method. Compared to organic fluorophore dyes, which are also used for tracing in the oil industry, quantum dots are more chemically stable, and their fluorescence intensity is 1-2 orders of magnitude higher (Saprykina, Ovchinnikov, 2018).

The use of quantum dots in the tracing technology is because of the large number of possible combinations in the synthesis of marker-reporters (more than 60), called signatures. At each stage or interval, a unique signature is used for the hydrocarbon and water phases of the formation fluid. To implement this solution, various types and combinations of marker-reporters 0.2-0.4 micron in size are first introduced into the proppant polymer coating, which gradually deteriorates upon contact with oil and water. The marked proppant is injected with the last pack in the volume of 15 tons (with an optional displacement of 5 tons with ordinary proppant). Over the period of multiple years, marker-reporters are washed out with water and oil and brought to the surface with the formation fluid flow. Well fluid samples taken from the wellhead undergo the sample preparation stage involving the separation of hydrocarbon and water phases using a demulsifier and centrifugation. Next, the separated hydrocarbon and water phases of the samples are automatically analyzed by flow cytometry using the GEOSPLIT hardware-software complex.

This method is based on the logging of dispersed media in the mode of the item-to-item analysis of elements of the dispersed phase using light scattering and fluorescence signals (Gurianov, Katashov, Ovchinnikov, 2017). The process of production logging using markers is presented on Figure 1.

Initially, a hydrodynamic focusing system is used in the microcapillary system, where, due to the pressure difference between the sample and the flowing fluid, the markers pass one by one through the flow cell in the laminar fluid flow. Next, the particles are irradiated in the liquid by lasers and the signals of light scattering (Figure 2) and fluorescence are indicated from each quantum dot or their combinations in the marker-reporters (Shapiro, 2003).

The parameters of the particles in the test liquid are recorded to isolate the qualitative and quantitative composition of the markers. The analytical hardware-software complex registers two types of light scattering: direct (low-angle) and lateral (Figure 3).

The direct light scattering detector is located along the laser beam behind the flow cell and registers the laser radiation, scattered at varying angles of 2-19 degrees. The intensity of light scattered at a small angle is proportional to the size of the particle. Larger particles scatter light more than small ones. The internal contents of the particles are optically inhomogeneous. The laser beam, passing through the particle, is repeatedly reflected, refracted and scattered in different directions. Registration of this radiation allows users to analyze the shape, size, and internal structure of the particle, which is displayed on Figure 4.

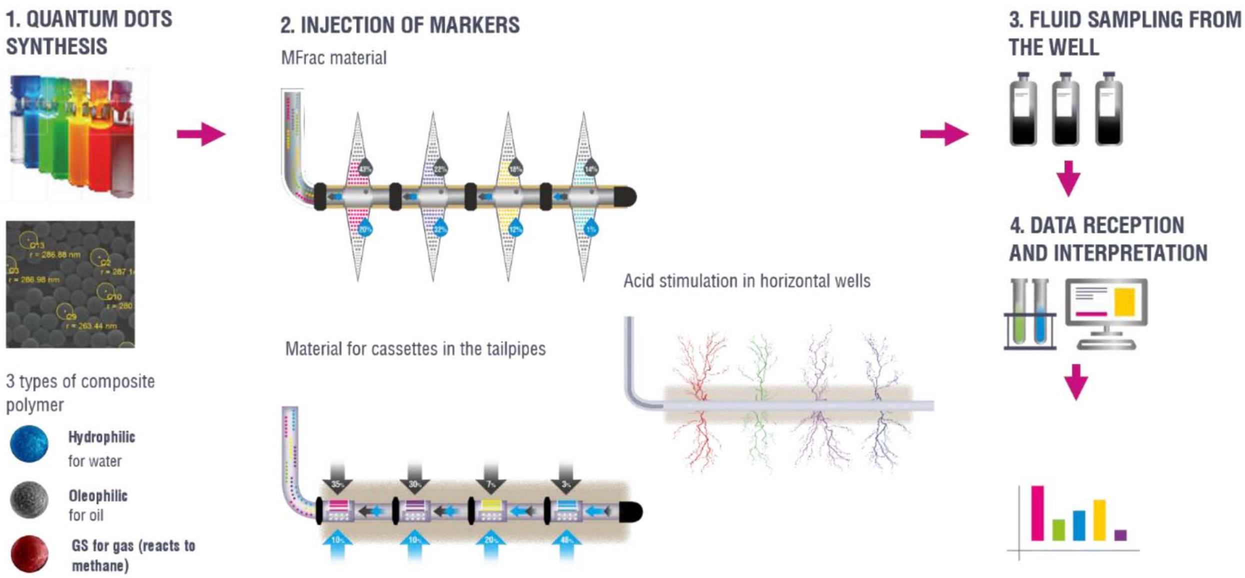

Figure 1—Process of Production Logging Using Markers

Figure 2—Quantum Dot Fluorescence Under Laser Irradiation

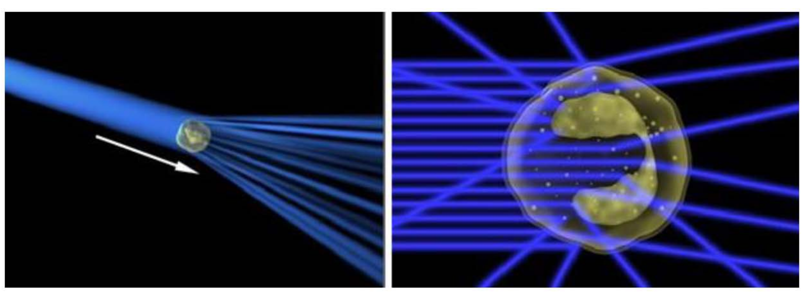

Figure 3—Direct and Lateral Light Scattering of a Particle

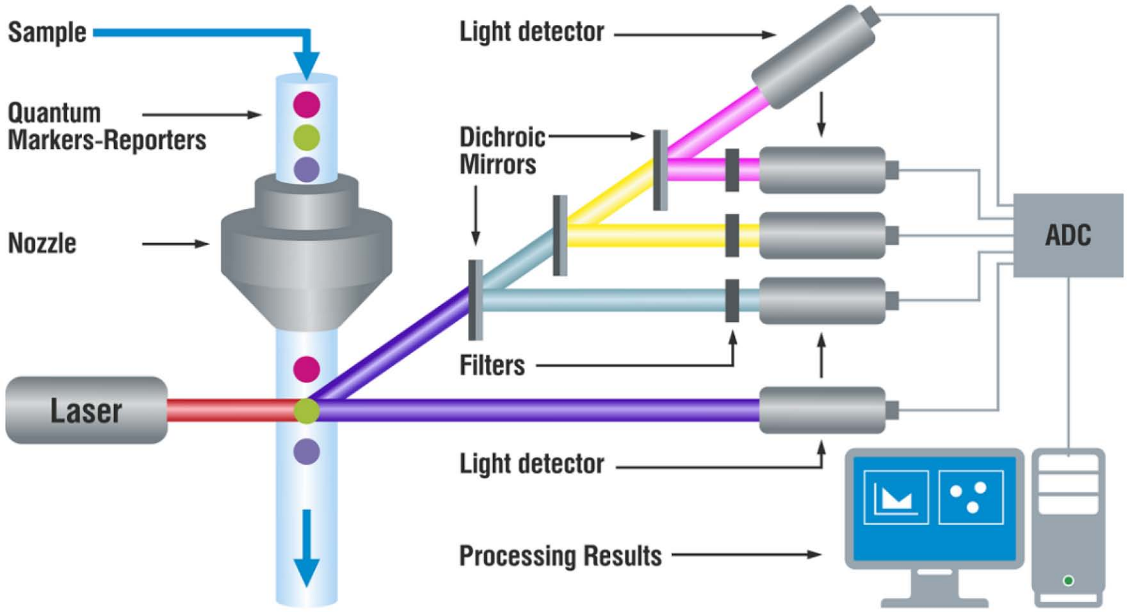

Figure 4—Scheme of the hardware-software complex GEOSPLIT operation

Because of the hardware-software complex operation, the events that are optical inhomogeneities in the optically homogeneous mobile phase are recorded. Since the used optical markers have a characteristic "glow," each in its own spectral region, the software allows each of the signatures used for the analysis to be separated among a large number of the "events" recorded by the hardware-software complex. The interpretation and identification of each signature is based on the following provisions.

Quantum dots are injected into markers both individually and in various combinations. Moreover, not only is their combination variable, but the concentration is variable as well. Thus, using three quantum dots of different optical characteristics in various combinations, as well as two different concentrations (high and low), a large number of signatures with different optical properties can be obtained (Gurianov, Katashov, Ovchinnikov, 2017).

There is some peculiarity inherent to the cytometric logging in the tracer-based technology because the number of markers of each code that are recorded depending on the intensity of their radiation at a fixed wavelength. Each marker signature corresponds to the characteristic area of the spectral space, which does not intersect with the characteristic areas of other quantum dot combinations. The software used for the optical identification of each code enables the isolation of their characteristic area in the spectral space (3D image) and the counting of the registered "events" in each area. The definition of the characteristic areas described above is carried out on the basis of laboratory experiments that simulate each signature separately, as well as their numerous combinations.

The data obtained are interpreted using the effective software and are visualized in the form of inflow schedules subject to hydraulic fracturing stages in time and accumulated oil and water flow rates at each stage.

First Experience

In 2016, Gazpromneft-STC LLC initiated a pilot project for the injection of marked proppant during 11-stage hydraulic fracturing into well 29340GS of the Priobskoye field. According to the results of the formation fluid samples analysis, the service company recorded the markers of codes 10 and 11, which, by coincidence, were not injected into this well. As a result, the technology was refined and strengthened in a number of areas, including quality control, production, improvement on existing methods, the introduction of new tools for data interpretation and identification of markers in formation fluids.

The process of technology application was divided into stages, which were carefully analyzed and experienced significant changes, with the results presented in Table 1.

Table 1—The process of technology implementation

NN	Stages	Status
1	Synthesis of quantum marker-reporters	Profound changes
2	Synthesis of polymer-coated marked proppant	Profound changes
3	Quality control of manufactured products	Implemented
4	MFrac under designer supervision	Implemented
5	Sampling according to the established schedule	Optimized
6	Delivery of samples to the laboratory	Optimized
7	Sample preparation	Profound changes
8	Instrumental tests	Profound changes
9	Data processing using method of machine-learning	Implemented
10	Verification and interpretation of results	Profound changes
11	Issue of reports to the Customer	Optimized

Stage 1. During thermobaric testing of the product under conditions close to the reservoir, insufficient thermal stability of quantum marker-reporters was noted, leading to the death of more than 60% of the markers during prolonged exposure to temperatures above 90C and a 30% loss of intensity of the response signal of quantum dots during prolonged thermal exposure. It was also noted that after thermal exposure, some signatures (codes) became quite difficult to distinguish. So, for example, the codes of markers 1 and 3 could be taken as one code under certain conditions. This is because prolonged exposure to high temperatures (> 100 ° C) leads to a decrease in the fluorescence intensity of some quantum dots (most often, with shorter wavelength – they are less stable). This is the case under conditions when the initial concentration of these signatures is not very high, and the composition of the oil fluid has specific parameters. For example, related to more viscous oil, it was necessary to develop a more complicated sample preparation procedure — the transfer of markers from oil to distilled water.

Also, more viscous oil has elevated the autofluorescence values of the components of the hydrocarbon phase, which leads to deformation of the area of the multidimensional parameter space characterizing the marker. This led to the convergence of the detection areas and the subsequent imposition of codes 1 and 3 on each other. This in turn makes their quantitative and qualitative determination difficult. To solve these problems, the procedure for synthesizing marker-reporters was modified to obtain a more stable product, changing the content of quantum dots in polymer spheres to improve the **accuracy** of determination. *For difficult-to-distinguish signatures, such as 1 and 3, the initial amounts of quantum dots in polymer spheres were increased, so that the changes caused by high temperatures would not complicate further analysis.*

Stage 2. In the basic version of the technology, the polymer coating of proppant containing markers reacted to water and oil simultaneously. That is, it was amphiphilic. At the same time, the release into the aqueous phase was an order of magnitude lower than seen in the oil phase, which introduced considerable error in the measurements and required correlations to be determined through calculations.

The chemical composition of proppant polymer coating was completely changed to create oleophilic (OF) and hydrophilic (HF) markers, which oriented the product along different phases of the formation fluid. Because water has a large surface tension at the interface, marker-reporters 0.2–0.4 microns in size cannot move from one phase to another — for them the phase boundary is an insurmountable obstacle. A remarkable example of this is the Water Strider, which can remain stable on the water surface due to this surface tension.

The possibility of the markers' transition from water to hydrocarbon phase of the fluid and back is determined by a set of various properties of these phases, such as composition, temperature, pressure, the presence of mechanical impurities, etc. These factors directly or indirectly affect the surface tension at the interface of the fluid. In addition, the ability to move markers also depends on the surface properties of the marker itself. Due to the high surface tension value, specific properties of the marker surface, such as transition are possible only under extreme conditions (particle speed is more than 20 m / s relative to the interface). This is confirmed through theoretical calculations and laboratory experiments.

As a result, the technology was fitted with a selective indicator for each part of the oil fluid. In addition, the new coating was more technologically advanced, which allowed us to increase the duration of the markers release from the proppant coating from one year in the basic version to three years with liquid flow rates of 200-250 tons per day. Figure 5 displays the interaction of the oleophilic proppant with water, which resulted in a clear lack of wetting. In this case, the hydrophilic proppant is wetted with water very well. During multi-stage hydraulic fracturing, 7.5 tons of hydrophilic and oleophilic proppant are mixed in the last pack.

Figure 5—Mixed Oleophilic (OF) and Hydrophilic (HF) Proppants

Images of updated marker-reporters with quantum dots using a VEGATESCAN scanning electronic microscope are presented on Figure 6.

Stage 3. It was noted that the production cycle for marked proppant production does not inherently ensure proper verification of product quality control, which therefore increased the risk of inconsistencies between the actual and stated marker signatures in the proppant coating. For the purpose of correction, the "Regulation on Production" and "Quality Management System" were revised. In addition to the already introduced standard studies of the strength and physical characteristics of proppant, a double quality check of the manufactured products was introduced, both in production and in the laboratory, as well as the selection of reference samples of marked proppant during the multi-stage hydraulic fracturing. That is, even before the actual injection into the well in the laboratory, samples are made from the marked proppant of the corresponding batch, confirming the actual compliance of signatures (codes) of the markers with the reference ones.

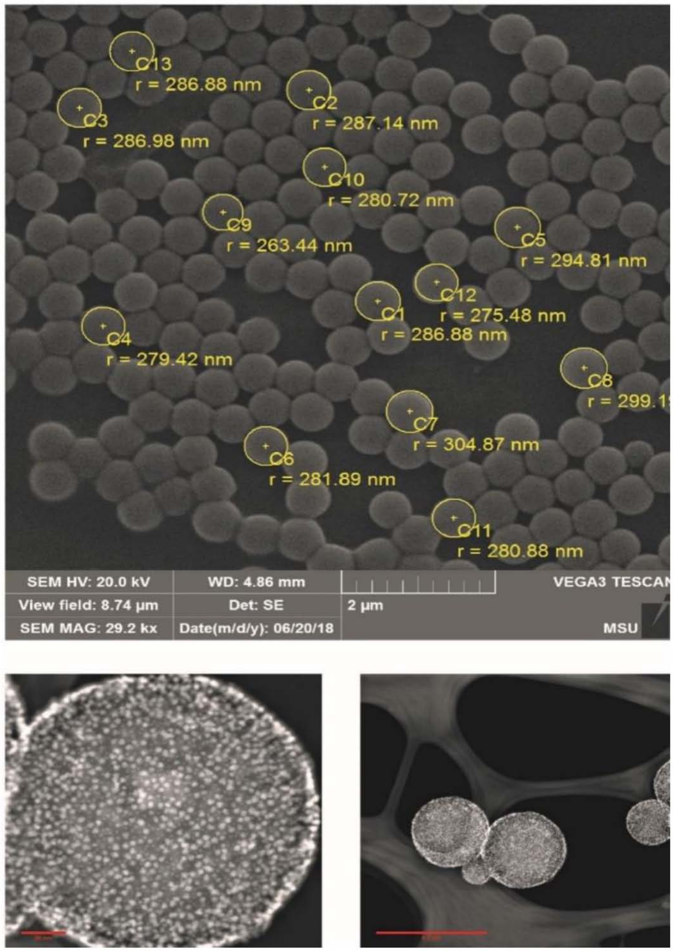

Figure 6—Images of updated marker-reporters with quantum dots using a VEGATESCAN scanning electronic microscope

Stage 4. Initially, the application of the technology implied the interpretation based on a single formation fluid sample in the volume of several liters. This did not ensure that the sample appropriately represented to entire population. To account for cork flow in the well, the effect of periodic ESP work and possible irregularity of well intervals, two typical sampling schedules were introduced; these are shown in Table 2. The samples were packed according to this schedule (Figure 7) to ensure reliable storage of fluid samples during transportation. Oil and frost proof labels were manufactured, and felt-tip pens were selected for filling them.

GEOSPLIT

customer / 客户			
oil field / 油田			
oil well # / 油井号			
Sampling date / 取样日期		Sampling time / 取样时间	
nozzle diameter, mm (if applicable) 喷嘴直径, 毫米(如果适用)		ESP frequency, Hz 电动潜水泵的频率，赫兹	
Current wellhead pressure (before choke restriction), MPa 当前井口压力(扼流圈限制前)，兆帕		Current wellhead pressure (after choke restriction), MPa 当前井口压力 (扼流圈限制后)，兆帕	
Sample taken by, Name, Last name 取样人员姓名			
Position / 职位			

Figure 7—Container for Formation Fluid Sampling

Table 2—Formation fluid sampling schedule at well No. ___ of the Vyngayakhinskoye during production logging using marked proppant.

Month	Date																															Total number of samples	Number of tests
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31/1		
March																																	
April					**10**					**10**										**10**										**10**		**40**	**4**
May															**10**															**10**		**20**	**2**
June																									**2**	**2**	**2**	**2**	**2**			**10**	**1**
July																																	
August																									**2**	**2**	**2**	**2**	**2**			**10**	**1**
September																																	
October																									**2**	**2**	**2**	**2**	**2**			**10**	**1**
November																																	
December																									**2**	**2**	**2**	**2**	**2**			**10**	**1**
January ‘20																																	
February‘20																									**2**	**2**	**2**	**2**	**2**			**10**	**1**
March ‘20																																	
April ‘20																									**2**	**2**	**2**	**2**	**2**			**10**	**1**
																															Total :	**120**	**12**

Notes:

1. By agreement with the Customer, the sampling dates may be changed.
2. The sample consists of one 1 litre container. The samples are taken at intervals of 1 hour.
3. During the first month after well commissioning, the samples are taken as follows:
• on the 5th day after the date of the well start-up, 10 samples are taken at intervals of 1 hour;
• on the 10th day after the date of the well start-up, 10 samples are taken at intervals of 1 hour;
• on the 20th day after the date of the well start-up, 10 samples are taken at intervals of 1 hour;
• on the 30th day after the date of the well start-up, 10 samples are taken at intervals of 1 hour;

4. During the second month after well commissioning, the following samples are taken:
• on the 15th day, 10 samples are taken at intervals of 1 hour;
• on the 30th day, 10 samples are taken at intervals of 1 hour;

5. In the third month after the well commissionimg, the following samples are taken:
• within 5 days (2 samples per day with an interval of 1 hour) - 25-29 of the month;
6. Next, the samples are taken 1 time in 2 months:
• within 5 days, 2 samples per day with an interval of 1 hour) - 25-29 of the month.
7. According to the results of the analysis of each pack, 10 samples are taken during the month, and an interim report is provided within 25 calendar days (but not earlier than 14 calendar days from the date the samples were received by the the laboratory).
At the end of the monitoring, a final report is submitted, which includes the final horizontal well production logging results.

The data of quantitative determination of the markers in the formation fluid samples are further visualized in the schedule shown in Figure 8, reflecting the percentage of the contribution of oil and water steps in the total well flow rate.

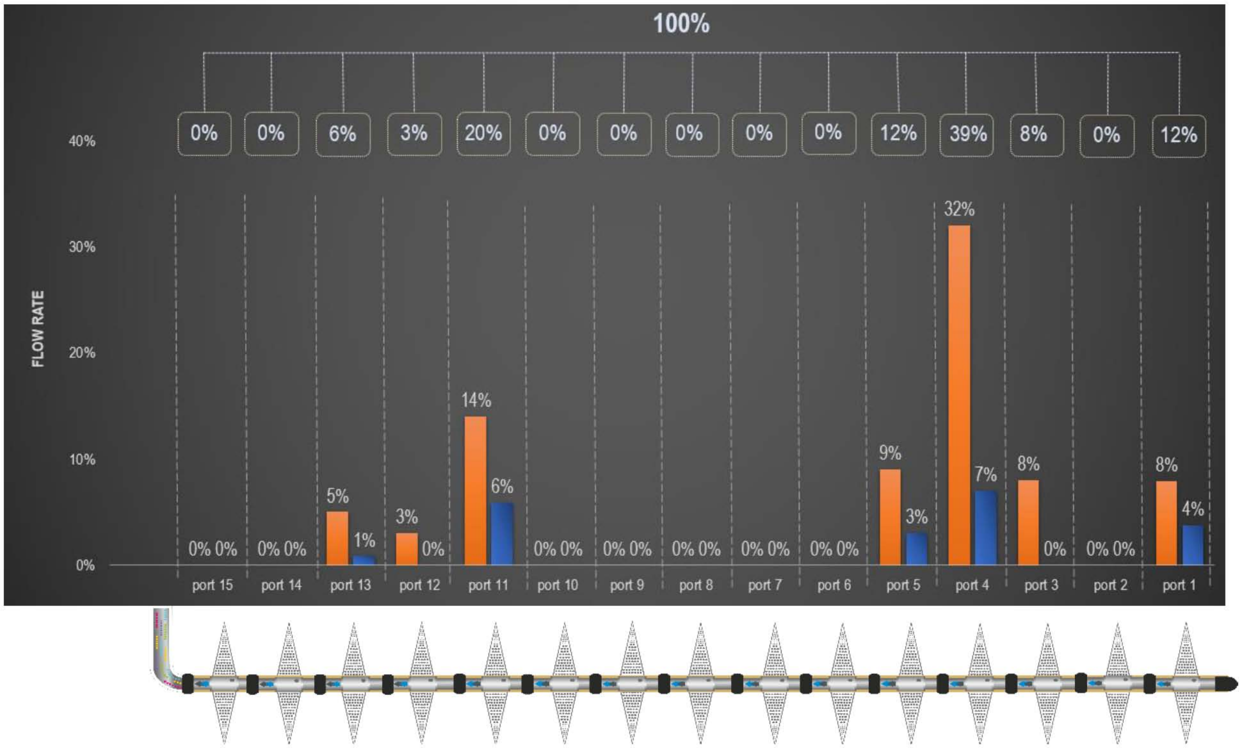

Figure 8—Distribution of the Accumulated Oil and Water Production by MFrac Stages

Figure 9 displays a typical visualization of productive intervals/stages operation dynamics with MFrac using markers.

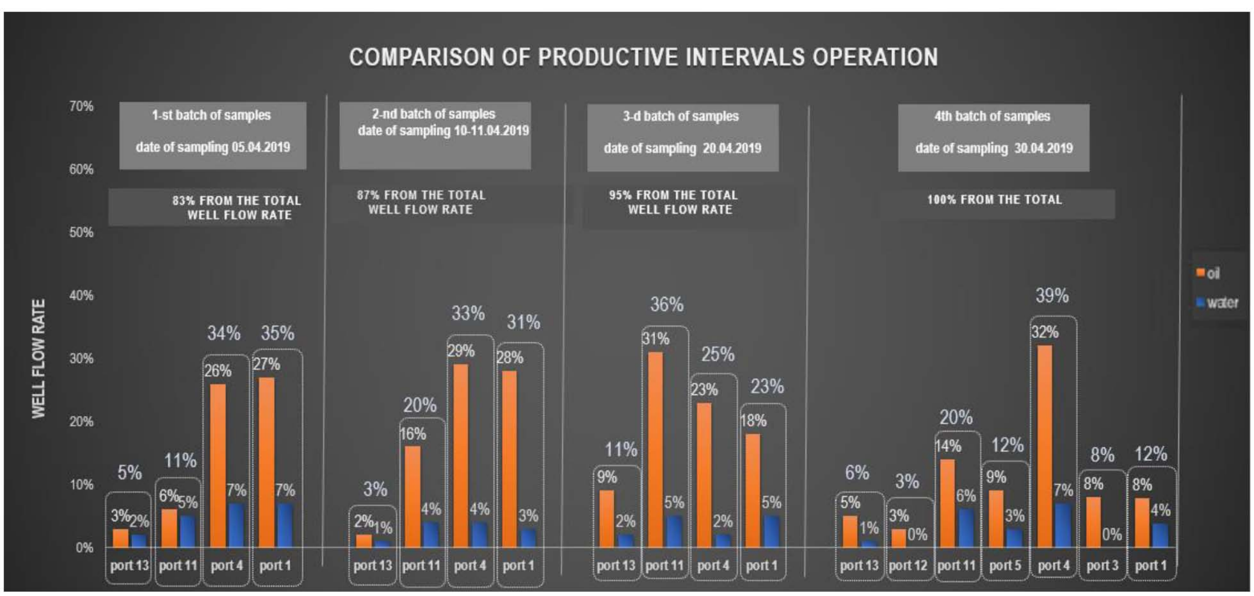

Figure 9—Dynamics of the Well Operation Productive Intervals Using Markers

Validation of the Production Logging Technology Using Markers

With the current development of the market, the increase in the volume of work and inclusion of tendering processes for the selection of technology producers for the oil producing companies is important in confirming the feasibility of the method. For this purpose, the specialists of Technological Centre "Bazhen" together with Gazpromneft-STC LLC developed and applied a program of blind tests. This program allows for confirmation of the stated characteristics of the identification accuracy of various marker codes in the formation fluid samples and aids in adjusting the correct selective operation of the water and hydrocarbon phases.

The procedure is shown on Figure 10.

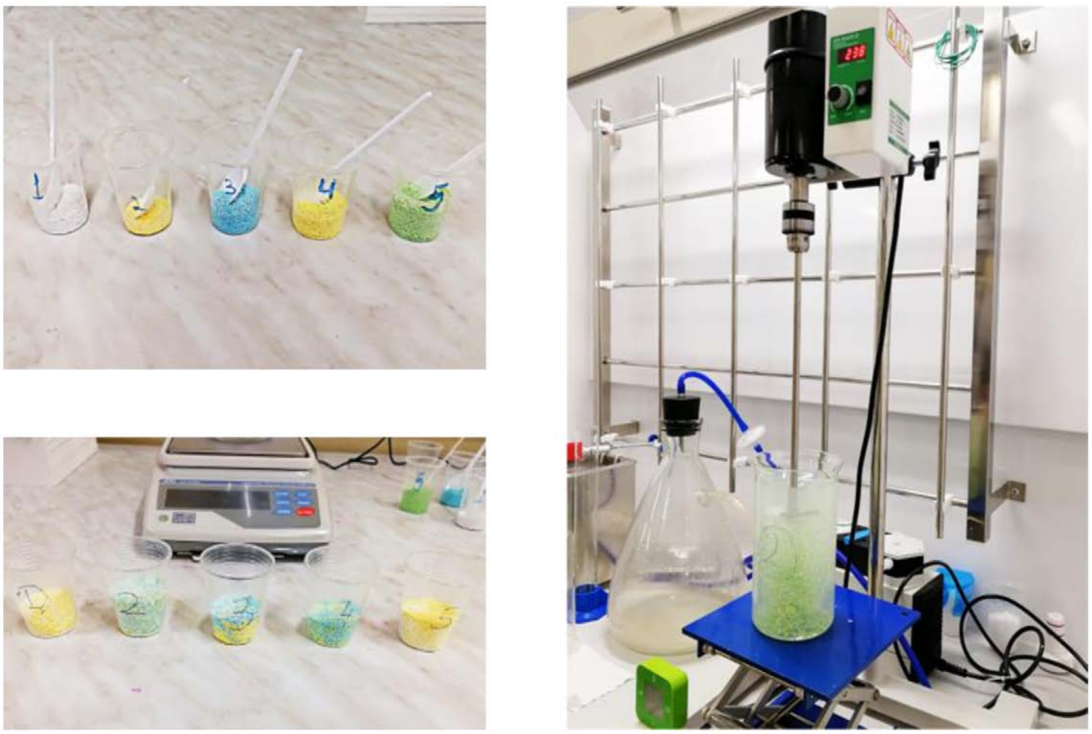

Figure 10—Blind tests procedure. Preparation of mixtures with different concentrations of the marked material and the procedure of marking the fluid for the technology performance test

A comparison of the data determined by the marker technology manufacturer and the actual data of the Customer's commission of the marked proppant are presented in Table 3.

Table 3—The results of the quantitative determination of markers using proppant

Identified in the samples by the manufacturer of marker-reporters				Actual data obtained during the commission of Customer 1					Discrepancy
Mixture	Cipher	Code	%	Mixture	Cipher	Code	%	Weight , g	%
№1	WT	1	**24**	№1	WT	1	**24.99**	249.95	**0.99**
	WG	2	**25**		WG	2	**25.34**	253.35	**0.34**
	WR	3	**16**		WR	3	**14.99**	149.98	**1.01**
	WU	4	**0**		WU	4	**0**	0	**-**
	WP	5	**35**		WP	5	**34.68**	346.88	**0.32**
	Total		**100**		Total		**100.00**	1000.16	**-**
№2	AR	6	**29**	№2	AR	6	**26.78**	273.76	**2.22**
	AQ	7	**18**		AQ	7	**18.16**	185.62	**0.16**
	AT	8	**11**		AT	8	**12.37**	126.47	**1.37**
	AY	9	**13**		AY	9	**12,32**	125.95	**0.68**
	AW	10	**29**		AW	10	**30.37**	310.5	**1.37**
	Total		**100**		Total		**100.00**	1022.3	**-**
Average discrepancy, %									**0.94**

Sample Preparation Procedure

The equipment used to identify the markers in formation fluid samples works with aqueous and nearly aqueous solutions. The actual fluid containing markers is oil and a mixture of oil and water is emulsion that can contain various impurities: sand, clay, salts, gas bubbles, and organic inhomogeneities. The procedure for sample preparation is aimed at transferring markers into distilled water to separate all the impurities without losing a significant number of markers. To solve this problem, a combination of various physicochemical methods is used: selective filtration, centrifugation, concentration, and sorption. As a result, a small test tube of pure liquid containing the high resistance marker-reporters from the selected liquid, schematically shown in Figure 11, is obtained. Experimental and laboratory work on the selection of complex methods for transferring the markers from formation fluid to a clean solution took 1.5 years, during which about 30 different techniques were tested. As a result, in 2019 the development team managed to achieve a result of no less than 90% of the markers.

Figure 11—Schematic transfer of markers from formation fluid to distilled water, identification and counting.

Implementation of Machine-Learning method

Each marker-reporter represents a point in the 15-dimensional space of coordinates on the images, reacting after laser irradiation with manifestation in different wavelengths. Manually processing this data using using only a hardware-software complex prevents the achievement of acceptable determination accuracy. With many signals and a large number of signatures in the analyzed fluid sample, the task of quantifying and counting markers manually becomes difficult to perform and requires a significant amount of time. In addition, it is impossible to completely exclude the errors caused by the "human factor." The developers of the marker technology proposed an innovative data processing approach based on artificial intelligence. The program created by the developers of marker technology is based on machine-learning using the "Random Forest" algorithm. Simply speaking, this process can be described as follows: initially, the neural network is trained on "referee" samples of marker-reporters, from which the so-called "decision tree" is built. At each depth stage, the parameters are sorted according to a certain parameter, for example, the excitation of a particle in a certain range of electromagnetic spectrum. The depth of the "tree" may be different for each instance. Software creates a large variety of "trees," all of which differ in structure (Louppe, 2015).

As a result, when passing through such a tree, the marker of the desired code falls into a strictly defined "basket." The algorithms now understand which basket each particular marker code should fall into. Then a mixture of many markers is examined on the created tree and sorted, i.e. the algorithm considers how many markers of which type were used in the mixture. Each tree makes its decision, or conditionally speaking, "votes" on the composition of the mixture, using the proppant injected into the formation fluid. This allows users to realize very high accuracy in data interpretation. In general, machine-learning algorithms enable the processing of a large data array with a given accuracy in a short time frame, while eliminating the "human factor" (Figure 12).

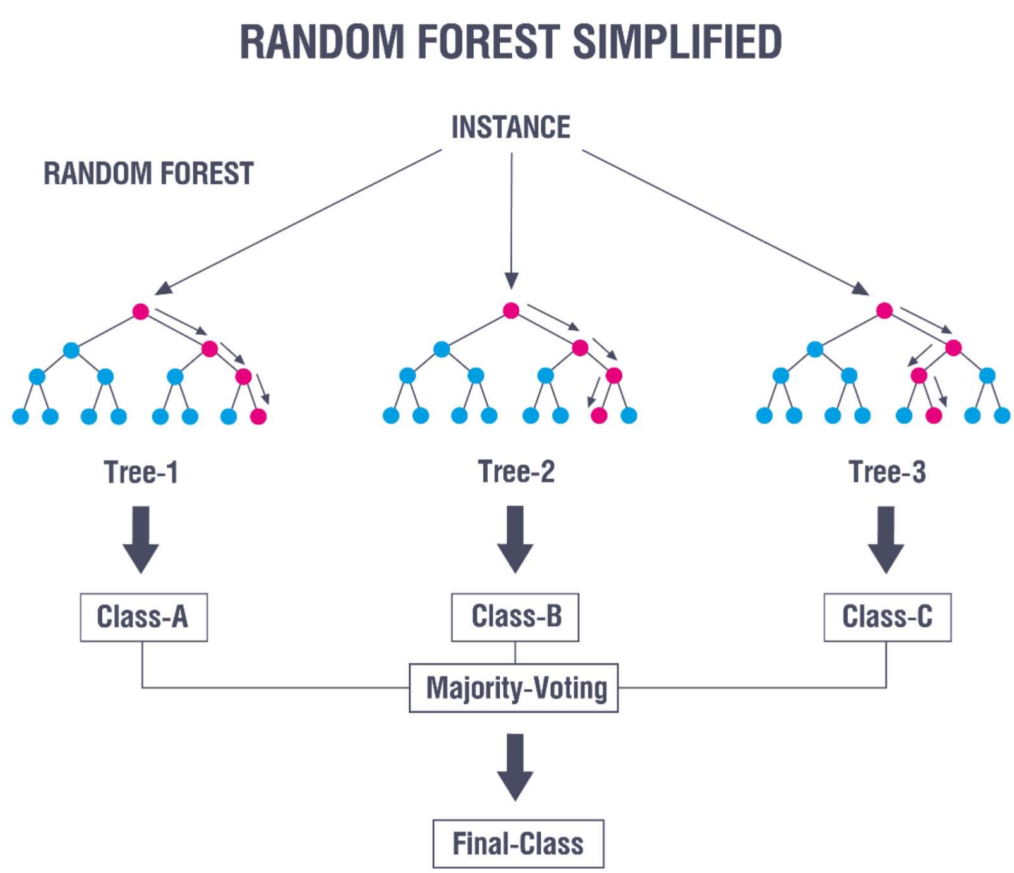

Figure 12—Principles of the algorithm "RandomForest" application for identification of the markers

Project Summary

The conducted complex of tests and field application lead to conclusions on the performance of horizontal wells production logging technology using markers and the actual opportunities for its development. By now, this technology has been successfully applied at 5 wells with multi-stage hydraulic fracturing (10-15 stages) within the Technological center "Bazhen":

- Field № 1 in Yamal-Nenets Autonomous Okrug (YNAO);
- Field № 2 in Khanty-Mansi Autonomous Okrug-Yugra (KhMAO-Yugra) – a successful comparison with PLT logging was performed;
- Field № 3 in YNAO - a successful comparison with PLT logging was performed;
- Field № 4 in KhMAO-Yugra;
- Field № 5 in KhMAO-Yugra.

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