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Dynamic Flow Monitoring in Horizontal Wells with High-Stage Mfrac in Conditions of Bazhen Formation

Valery Borisovich Karpov, Yugranefteprom LLC; Arsentiy Alexeyevich Ryazanov, RITEK LLC; Nikolay Vasilyevich Parshin, Yugranefteprom LLC; Dmitry Igorevich Sleptsov, RITEK LLC; Denis Vagizovich Kashapov, Mavlyutov Institute of Mechanics, Ufa Investigation Center, RAS; Kirill Nikolaevich Ovchinnikov, Evgeny Aleksandrovich Malyavko, Ekaterina Vladimirovna Potapova, and Anton Vitalyevich Buyanov, GeoSplit LLC

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SUMMARY

Currently, there is a growing tendency to involve unconventionals in development, therefore drilling, completion and production stimulation technologies are being intensively developed. Cost-effective development of hard-to-recover reserves (HTR) is possible only with the involvement of horizontal drilling and multi-zone hydraulic fracturing.

Due to the fact that conventional methods of PLT of horizontal wells for traditional reservoirs have a number of difficulties when operating on unconventionals, alternative methods for well surveying using flow indicators are increasingly in demand that allow multiphase monitoring of long-term multiphase inflow along a horizontal hole without involving additional equipment, well kill, etc.

The objective of this article was to obtain confirmation on the profile distribution and inflow composition after the MSHF operation for further well intervention planning in the main unconventional of the Russian Federation – the Bazhenov formation.

In a study, the inflow was monitored for oil and water phases in horizontal wells with multistage hydraulic fracturing (from 9 to 15 stages) and the use of the marked proppant. The technology of marker studies of horizontal wells consists in a single placement of high-precision indicators of fluid inflow in hydraulic fractures. After the completion of the MSHF field operation and putting the well into operation, sampling of the reservoir fluid from the wellhead was carried out and they were analyzed on the quantitative distribution of markers of each code corresponding to the interval distribution of oil and water flow rates.

The monitoring of marked wells was carried out periodically for several months. The flow profiles of horizontal holes were constructed on the basis of analysis of samples and analytical data obtained. The results of the work allowed to analyze efficiency of stimulation of horizontal wells for each of the stages of hydraulic fracturing.

Unlike traditional research methods, the main advantage of the presented technology for monitoring the horizontal inflow profile is the lack of need for using special means of device delivery, the use of

the technology is not fraught with risks of seizure of equipment and ambiguity of interpretation. It is also important to note that this technology allows monitoring continuously for several years without additional measures.

Comparison of research and monitoring methods is shown in table No. 1.

Table No. 1—Comparison of the characteristics of various types of monitoring of well inflows

Type of monitoring	Classical set of PLT using CT	Distributed fiber optic sensors for online monitoring	Marked proppant
Monitoring period	A few hours	Up to several years (depending on the quality of the optical material and the number of removal of solid particles from the rock)	Hydrophilic, oleophilic, gas – more than 3 years (depending on conditions)
The need to stop or change the well operation mode	Yes	No	No
Bench tests	Yes	No	Yes
Number of studies per year	1-2	Continuous monitoring	6-12 (selectively upon customer request)
Laboratory	Not applicable	Not applicable	Yes
Multi-hole, multilateral wells or wells with a large distance of the bottom from the vertical	Opportunities are limited	Yes	Yes
Use in cemented shanks	Yes	No	Yes
Use in old/new wells	Yes	For new wells	Yes
Use in open holes	Yes (there are restrictions)	No	Yes (there are restrictions)
Assessment of the quality of bottom-hole or hydraulic fracturing treatment	No	KO – Yes Hydraulic fracturing – limited	Yes
The possibility of increasing the efficiency of field development based on the results	Yes	Yes	Yes
Limitations of the technology	Availability of a horizontal hole; Risks of downhole operations;	The complex process of running in hole; Repair and maintenance is required; Not a mass decision	Limited use in high-viscosity oil; Depends on the success of the hydraulic fracturing operation

INTRODUCTION

In the modern conditions of the development of the oil and gas industry, there is a long-term movement to increase the share of horizontal drilling, while there is an increase in the total number of horizontal wells introduced from drilling horizontal wells of the average length of the horizontal hole, as well as the number of MSHF stages (Rudnitsky, 2017). As a general rule, the subsurface user does not have reliable analytical information on the actual distribution of the formation fluid inflow profile in horizontal holes. Traditional research methods require stopping the operation of the well, pulling the downhole pumping equipment, numerous costs for the preparation and conduct of well logging with CT, which is associated with technical difficulties, risks of sticking and loss of tools in the well.

Therefore, in modern realities there is a shortage of tools to justify the optimal length of horizontal holes, the number of MSHF stages for the effective solution of the problems of production and development of fields operated using horizontal wells. Moreover, difficulties arise when evaluating the efficiency of the RPM system.

Alternative methods – technologies for well marker studies – are becoming increasingly common in the global oil industry. The obvious advantages of these methods include the absence of the need to stop well operation and perform downhole operations during research, as well as the ability to continuously obtain data on the selective influx of water and oil from each interval over a longer period of time.

DESCRIPTION OF THE MARKER RESEARCH TECHNOLOGY USED ON WELLS WITH EXTENDED HORIZONTAL HOLES OPENING THE HARD-TO-RECOVER RESERVES SITES

The technology of marker research of horizontal wells is based on the use of quantum marker reporters, which are high-precision indicators of fluid inflow [2]. This technology consists in placing high-precision indicators of fluid inflow in artificially created conducting hydraulic fractures (half-length up to 600 m). After the completion of the MSHF field operation and putting the well into operation, sampling of the reservoir fluid from the wellhead is carried out and the quantitative distribution of markers of each code corresponding to the interval distribution of oil and water flow rates is analyzed.

Marker-reporters are polymeric microsphere created from quantum dots (figure 1). Various combinations of quantum dots form the code (signature) of the marker.

The technology involves the placement of markers in the polymer coating of proppant, which is pumped into the formation during a multi-stage hydraulic fracturing (Guryanov, Katashov, Ovchinnikov, 2017). Figure 1 shows a grain of marked proppant with markers sewn into the polymer coating.

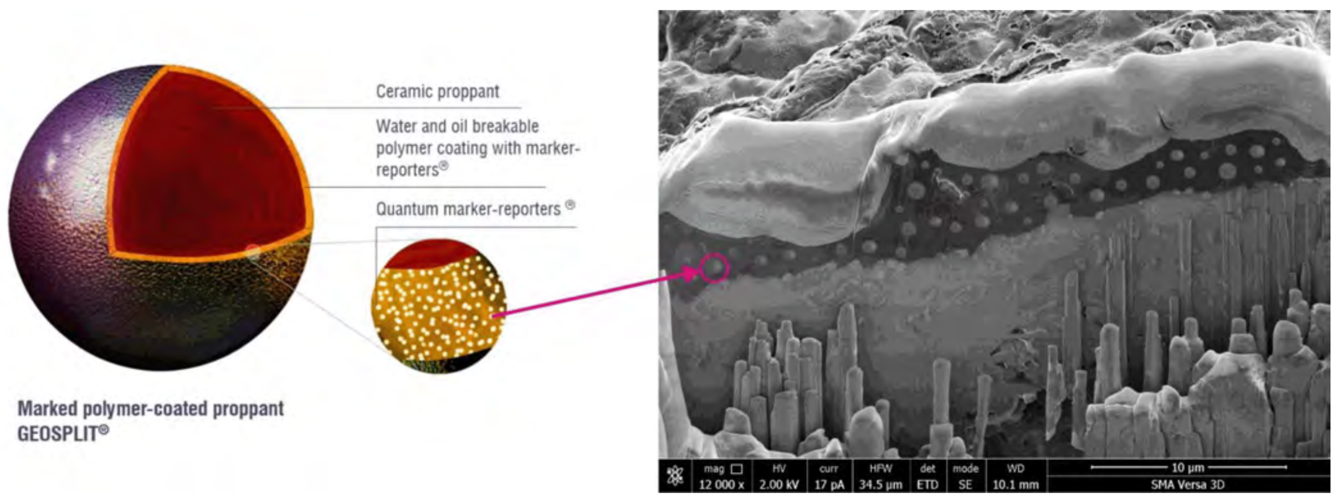


Figure 1—Grain of marked polymer coated proppant with quantum marker-reporters

When conducting multi-stage hydraulic fracturing, proppant is pumped into each stage, marked with a specific code, the last proppant pack to ensure maximum contact when washing the formation fluid coming from the formation into the well.

Marked proppant has three types of polymer coating – oleophilic focused on interaction with oil and hydrophilic focused on interaction with water.

According to the plan, 15 tons of marked proppant are pumped into each MSHF stage, which is evenly mixed in the ratio of 50 % hydrophilic (oriented to the water phase) and 50 % oleophilic (oriented to the oil phase).

During the subsequent long period of the well performance, the marker-reporters are gradually washed out with water or oil and transported by the reservoir fluid flow to the well-head. Marker-reporters are released both in the hydrocarbon and aqueous phases of the formation fluid.

After the completion of the MSHF field operation and putting the well into operation, periodic sampling of the formation fluid from the wellhead was carried out, after which the samples were transported to the research laboratory for analysis. At the initial stage, a sample preparation is carried out in the laboratory, as a result of which the aqueous and hydrocarbon phases are separated, and then separately analyzed in the analytical hardware and software suit. In this complex, a small-diameter fluid flow is formed (figure 2). In this flow, the markers are lined up, the passing stream is irradiated with a laser and the marker of each code is identified individually by the light scattering signal –direct and lateral. Thus, the analysis of the total volume of the received samples allows to identify the quantitative ratio of the port operation by phase (water and oil) in the total flow rate.

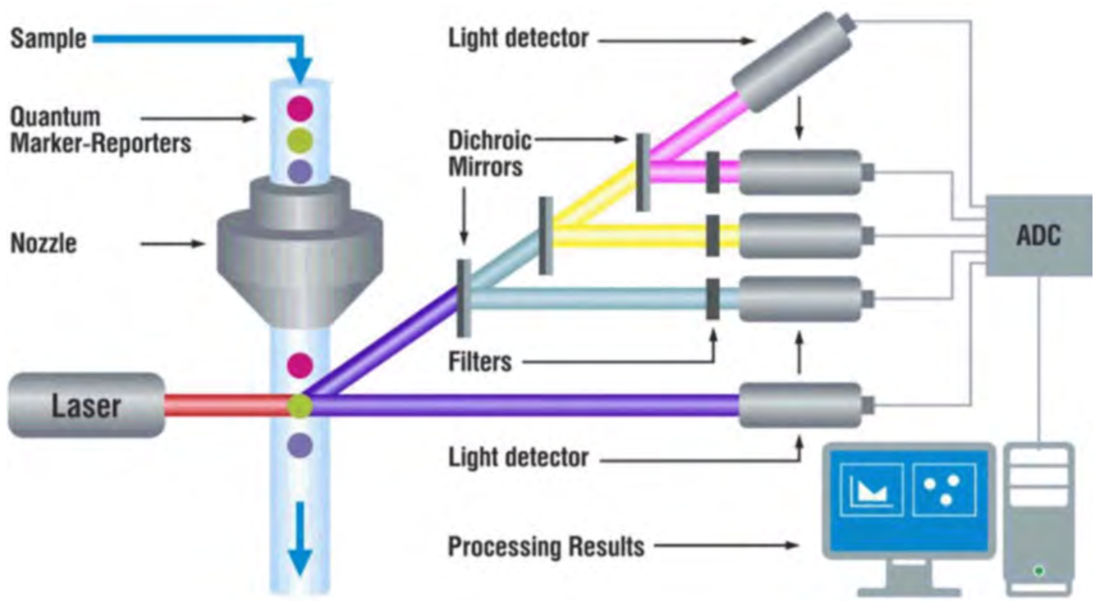


Figure 2—Analytical hardware and software suit that implements the flow cytometry method

One of the key elements of the technology is the use of machine learning methods, which are characterized by training in the process of applying solutions to many similar problems. Studies of horizontal wells involve working with large amounts of data. For example, information on the identification of each marker-reporter is a cloud in a 15-dimensional coordinate space, so the manual calculation method will be very labour-intensive. Consequently, the technology of marker diagnostics uses specialized intelligent software based on machine learning using the Random Forest algorithm.

The principle of action can be described as follows: initially, the neural network is trained on standard samples of marker-reporters, and a "decision tree" is built where parameters are sorted at each stage of the depth (for example, whether the particle is green or not). A huge number of such trees that differ in structure are created. As a result, passing through this tree, the marker of the right code falls into a strictly defined "basket". After training, the algorithms understand which "basket" each particular code should fall into. Then a mixture of a large number of markers passes through the entire created tree and is sorted, that is, the algorithm calculates the specific number of markers of each type in the mixture (figure 3).

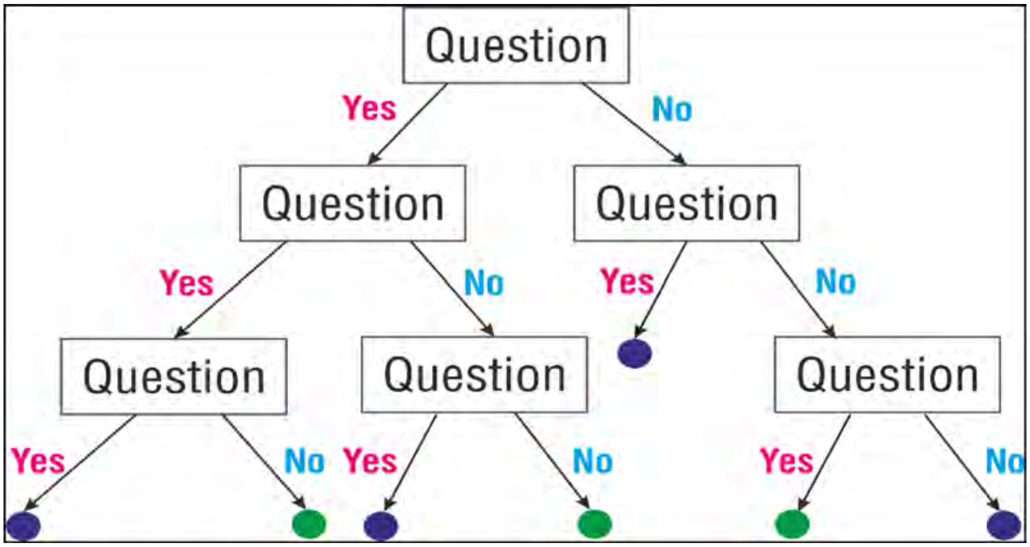


Figure 3—Algorithm of machine learning and building a decision tree

In general, machine learning algorithms allow to process a large amount of data with a given accuracy in a short time frame, while eliminating errors associated with the "human factor". Therefore, this algorithm is a high-precision and fast method for analyzing received samples.

DESCRIPTION OF THE OBJECT OF RESEARCH

The Bazhenov formation is a source rock assemblage bedding in Western Siberia from Kazakhstan border to the Kara Sea and has an area of about 1 million km^2. Extremely low values of matrix formation permeability ~ 0.01 mD and average BF depth about 30 m are typical for BF. Due to the low permeability of the formation, as well as the low oil-saturated thickness of the formation ~10 m, the development of the BF formations has long remained unprofitable for achieving industrial oil inflows.

Multi-stage hydraulic fracturing (MSHF) is the main effective method of HC recovery from the source rocks. HTR are fractured due to complexity of geology structure of the site under study, presence of natural fracture zones, abnormally high reservoir pressure (AHRP), low porosity & permeability (RQ), variable along the horizon distribution of wells with dramatically different production rate i.e. sweet spots, as well as high decline rates during the year after MSHF and so on. It differs fundamentally from operations in conventional formations. The use of specialized treatment plans for MHF to create long half-length hydraulic fractures involves the use of high-speed injections (Q~10 m^3/min) and a large volume of low-viscosity fluid used with small fraction proppants to transfer the grains inward during the initiation of rock fracture, which contributes to an increase in the area of drainage, and, consequently, HC production.

From the point of view of petrophysics, the Bazhenov formation at Sredne-Nazymskoye oilfield, where RITEK conducts multi-stage fracturing operations, consists of several packs: pack No. II has the highest rates of movable oil and porosity, and therefore the development guideline is directed to this site.

RESULTS OF ANALYSIS OF LONG-TERM MARKER DIAGNOSTIC OF FLOW PROFILES

Two horizontal wells No. 113G and No. 113-1G, which are located in close proximity to each other (figure 4(A)), as well as another well No. 115G, located on another well pad and opening the same oil source rocks (figure 4(B)), were considered as targets of the study. The target productive formation YU-K(0-1) of the well belongs to the Jurassic sediments and has an average formation pressure of about 300 Atm over the site and a temperature of 117°C.

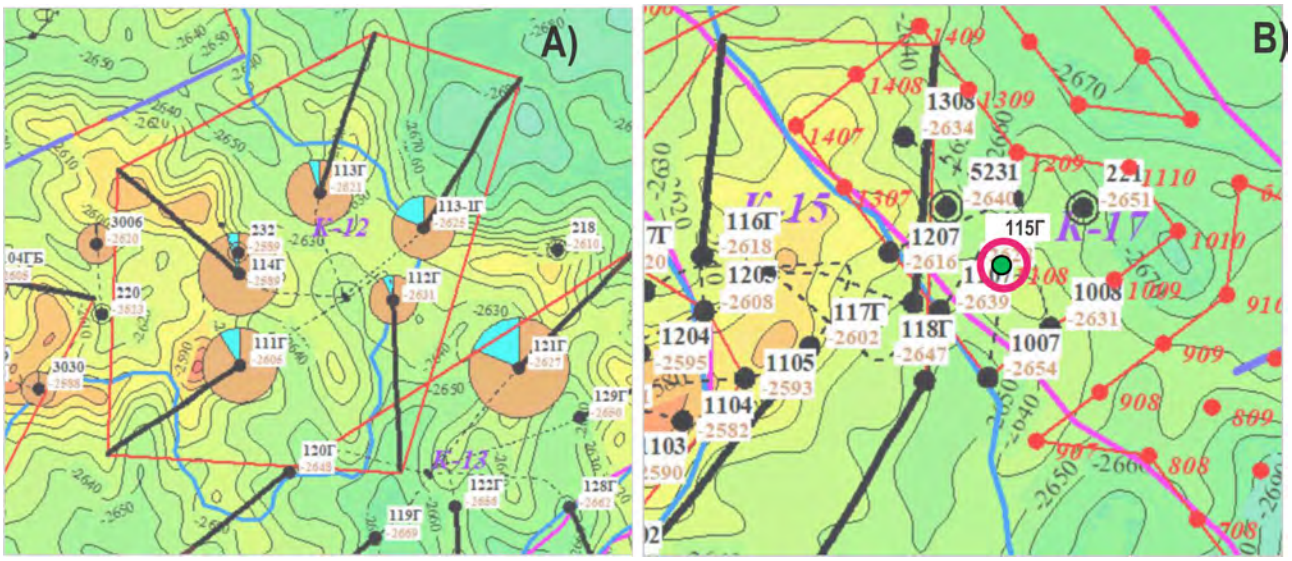


Figure 4—location of the studied wells A) well pad 12; B) well pad 15

First of all, consider the well 115G. Initially, it was planned to carry out a 15-stage hydraulic fracturing, but for some reason, in fact, only the first 10 stages were performed.

With the exception of stages 4 and 5, these stages are in the target treatment zone. The MHF operation performed is presented in table No. 2. It should be noted that the marked proppant was supplied at the last stage of injection.

Table No. 2.—MSHF Implementation Plan

Stage No.	Flow, m³ / min	V_{fluid}, m³	$Proppant_{Mass}$, t	20/40	16/20 (marked)	Flow, concentration kg / m³
1–5, 9–15	8	1,400	60	45	15	200
6–8	8	1,370	90	75	15	200

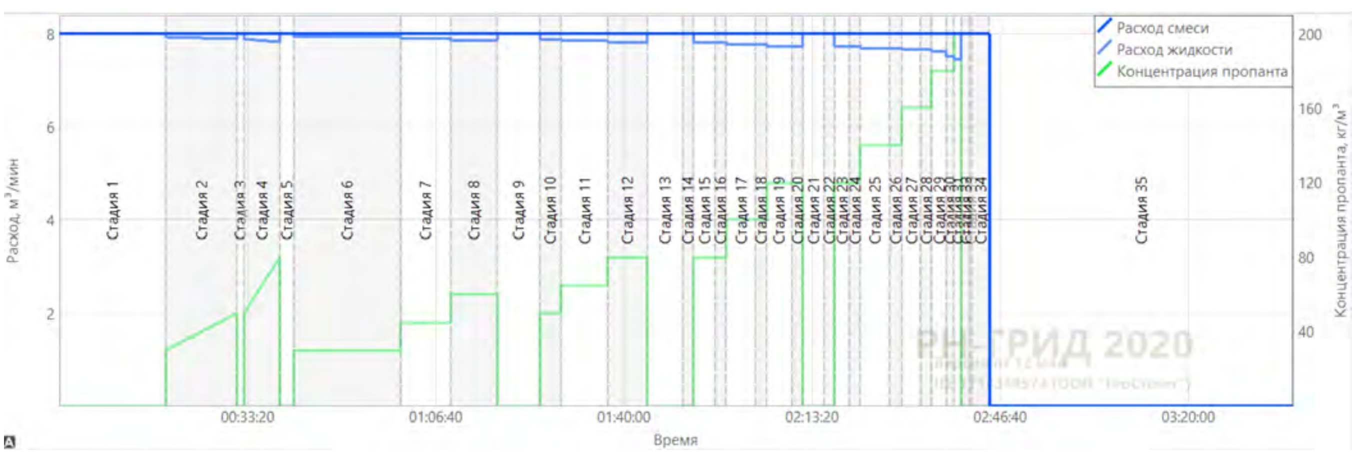


Figure 5—Hydraulic fracturing operation plan for stages 1-5, 9-15

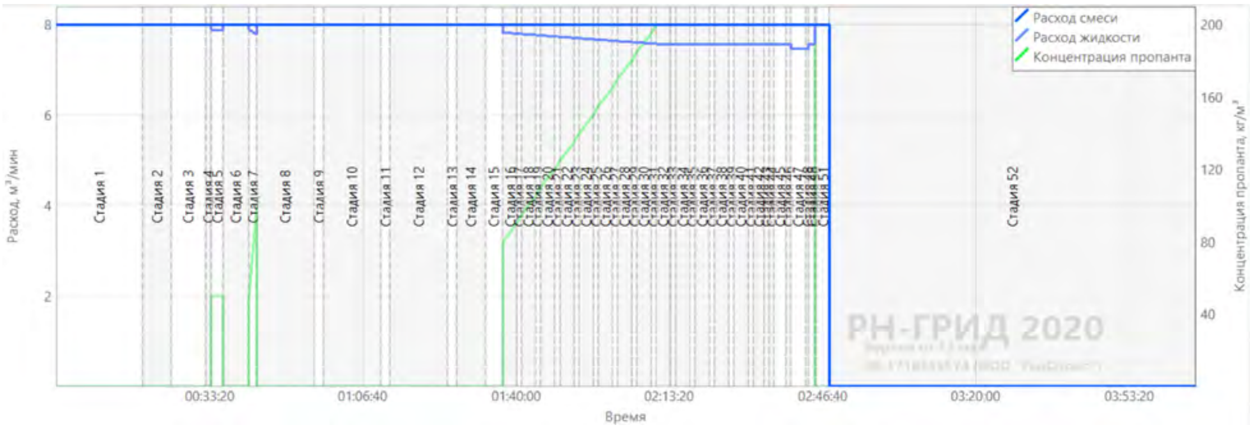


Figure 6—Hydraulic fracturing operation plan for stages 6-8

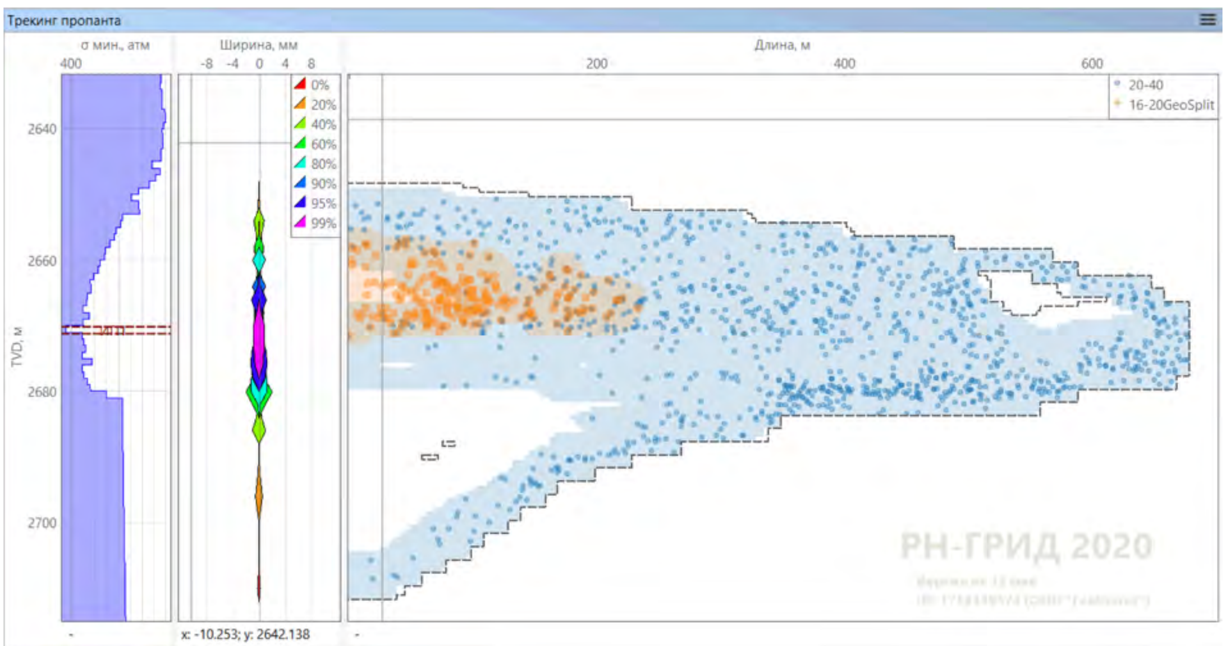


Figure 7—Geometry of the hydraulic fracture and proppant placement for stages 1-5, 9-15

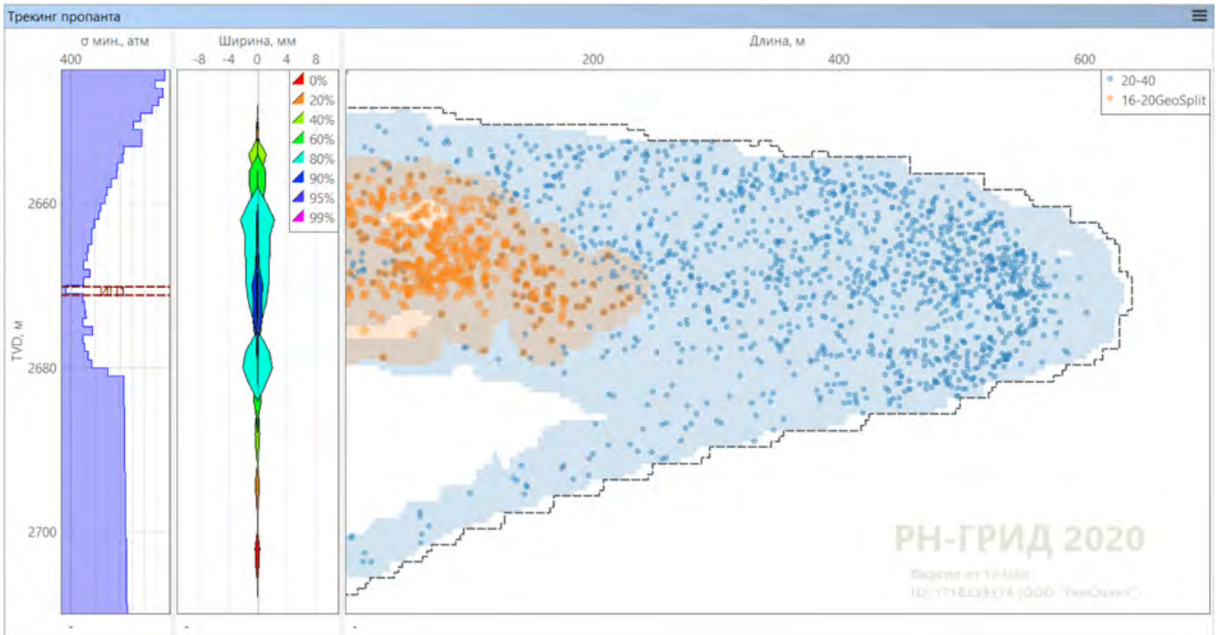


Figure 8—Geometry of the hydraulic fracture and proppant placement for stages 6-8

The results of MSHF operations are presented in Table 3.

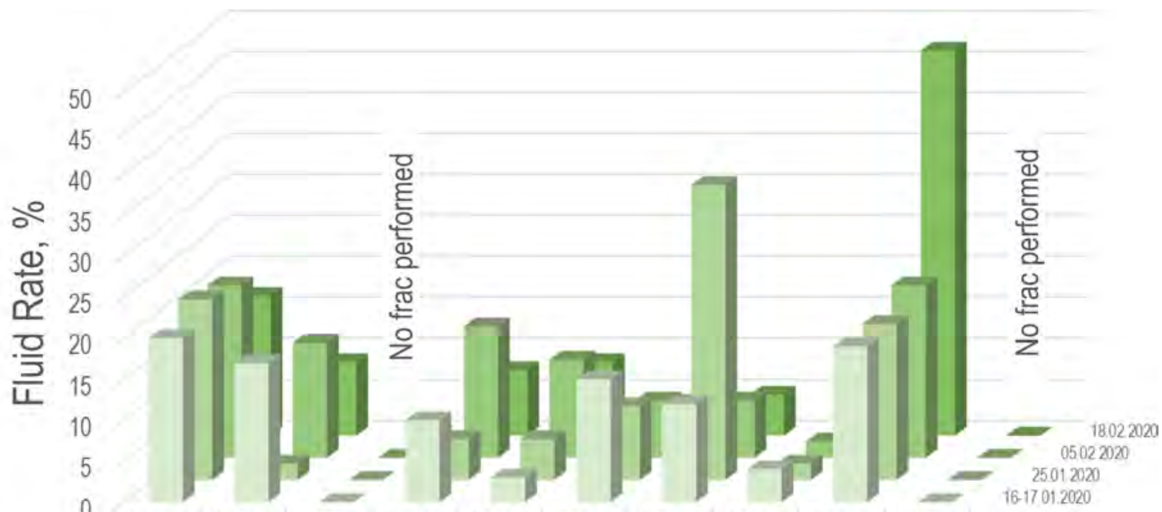
Table 3—Summary Data on MSHF at the 115G Well

No.	Problem	Plan	Proppant Mass	20/40	GS
1	STOP	60	11.5	11.5	0
2	Transition to the flush stage, flush	60	11.5	5.5	4.5
3	Hydraulic fracturing+	60	60	44	15
4	Hydraulic fracturing+	60	60	44	15
5	Hydraulic fracturing+	60	60	45	15
6	Hydraulic fracturing+	90	90	75	15
7	Hydraulic fracturing+	90	90	75	15
8	STOP	90	40	40	0
9	Hydraulic fracturing+	60	60	45	15
10	STOP	60	43	39	4
11	Cancellation	60	-	-	-
12	Cancellation	60	-	-	-
13	Cancellation	60	-	-	-
14	Cancellation	60	-	-	-
15	Cancellation	60	-	-	-

The well flow profile is uneven over the course of the study. Ports 2, 4, and 10 make the greatest contribution.

In the first month of the study, there was a significant decrease in the water cut for the selected samples, which is probably due to fracturing fluid flow back, after which there was a low level of water component in the inflow, and it remained unchanged during the study.

It is noteworthy that the dynamics of changes in the flow profile correlates fairly well with historical events in the well under consideration: the first sampling was performed on a small diameter choke (7 mm), then it was increased to 8 mm, the third (05.02.2020) and fourth (18.02.2020) sampling occurred during the time period of operation, when there was a choke with a diameter of 10 mm, while the flow rate of fluid increased from 160 m^3/day to 200 m^3/day. In general, the flow back of almost the entire fractured area is noted.



	10 port	9 port	8 port	7 port	6 port	5 port	4 port	3 port	2 port	1 port
16-17.01.2020	20	17	0	10	3	15	12	4	19	0
25.01.2020	22	2	0	5	5	9	36	2	19	0
05.02.2020	21	14	0	16	12	7	7	2	21	0
18.02.2020	17	9	0	8	9	4	5	1	47	0

Figure 9—Dynamics of the MSHF ports of the 115G well

With the exception of port 3, all ports contributed to the well operation. A possible reason for the low inflow of port 3 is that the interval reveals a zone with degraded filtration properties determined by the results of interpretation of logging during drilling.

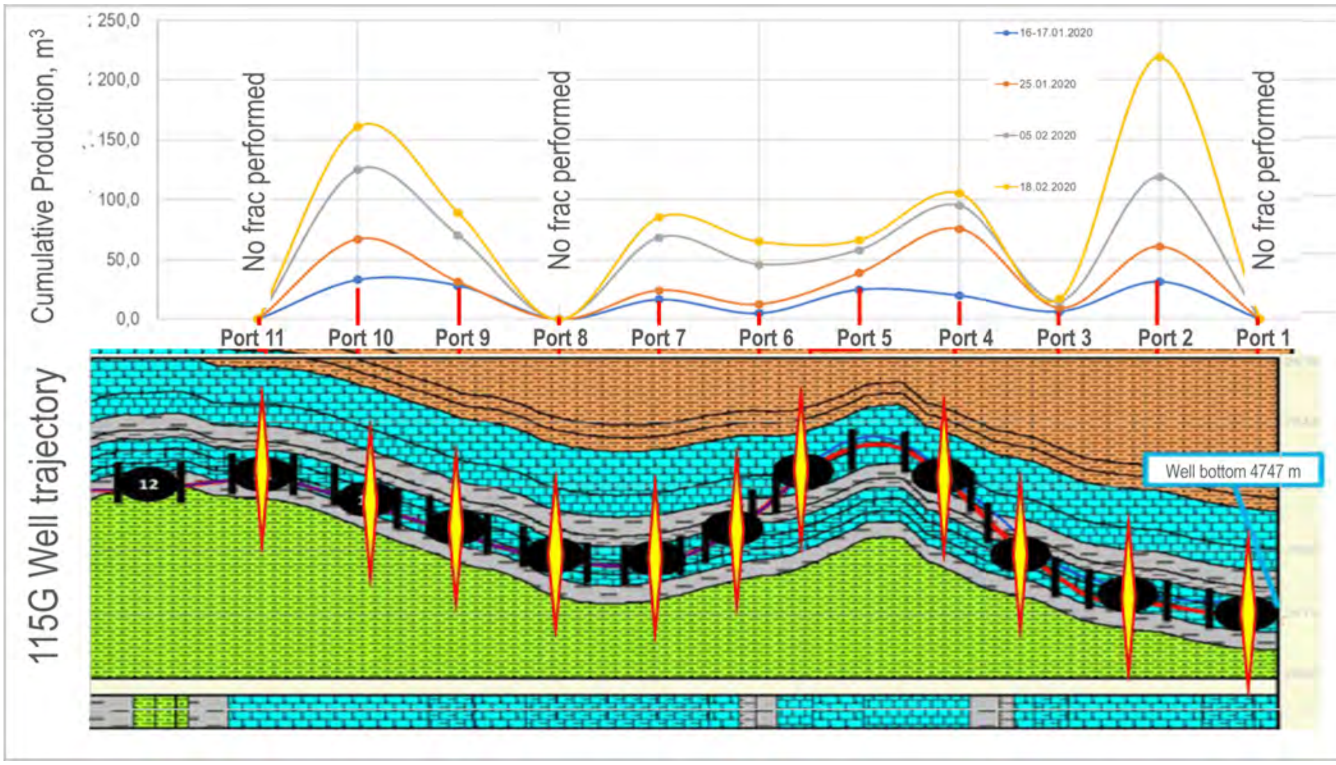


Figure 10—Distribution of the inflow profile based on the results of marker studies at the 115G well

A probable reason for the effective production of the "toe" part of the horizontal hole (port # 2), as well as the central section of the well (ports # 6, 7) is associated with an increase in the technological mode of the well operation by increasing the diameter of the choke to 10 mm (Figure 10).

The analysis of the 113G well was performed in the same way. A 15-stage MSHF operation was also planned and implemented there.

All stages are located in the target treatment zone. The Customer agreed to conduct the MSHF operation summarized in Table 4. Figure 11 shows data on the flow, concentration, and supply of propane. Marked proppant is served at the penultimate stage, followed by the flush by usual ceramic proppant of the 20/40 fraction weighing 2 t.

Table 4—MSHF implementation Plan

Stage No.	Flow, m^3 / min	V_{fluid}, m^3	$Proppant_{Mass}$, t	20/40	20/40 (marked)	Supply, concentration kg / m^3
1–15	8	1,230	90	75	15	200

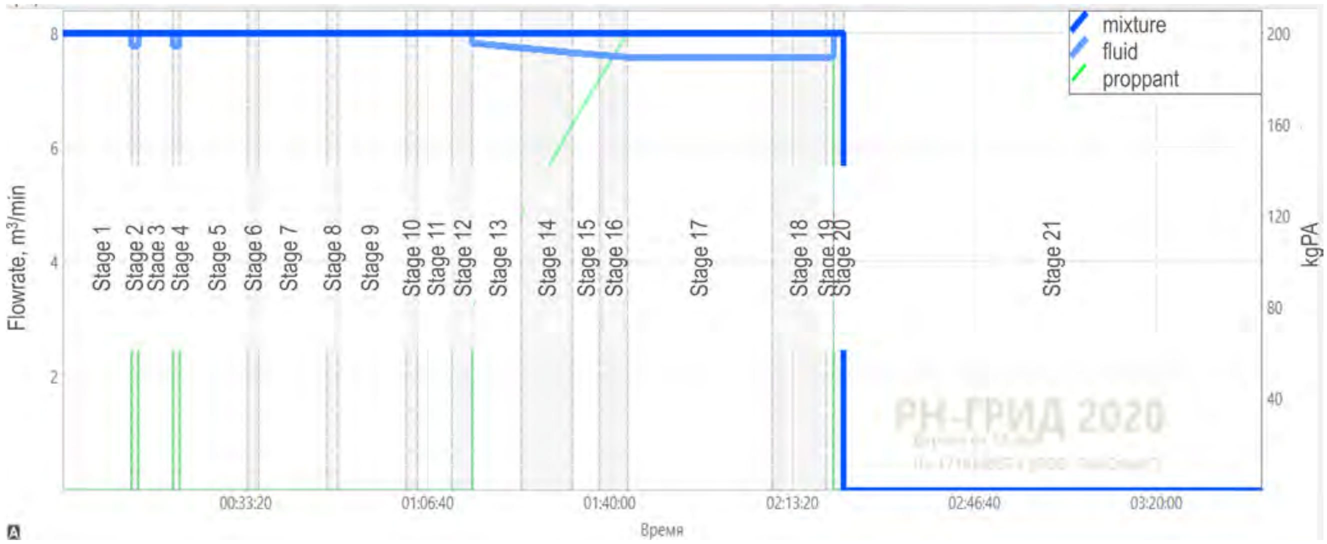


Figure 11—Hydraulic fracturing operation plan for stages 1-15

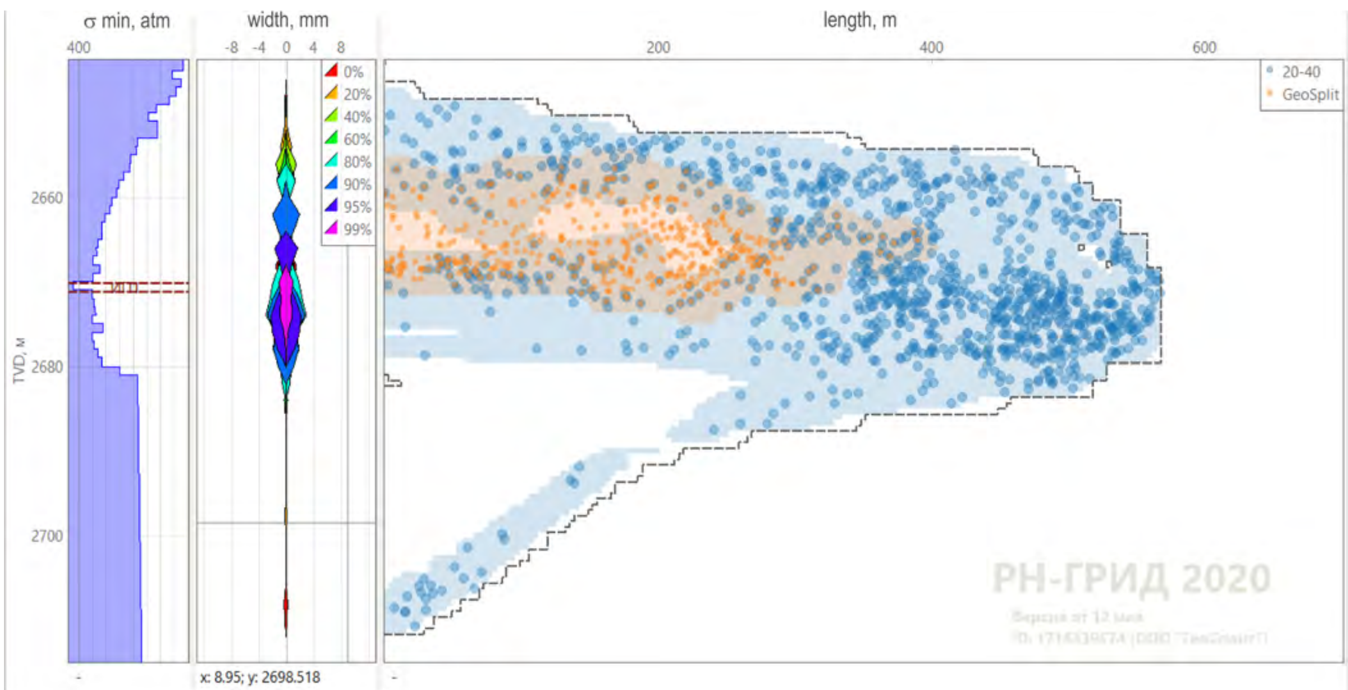
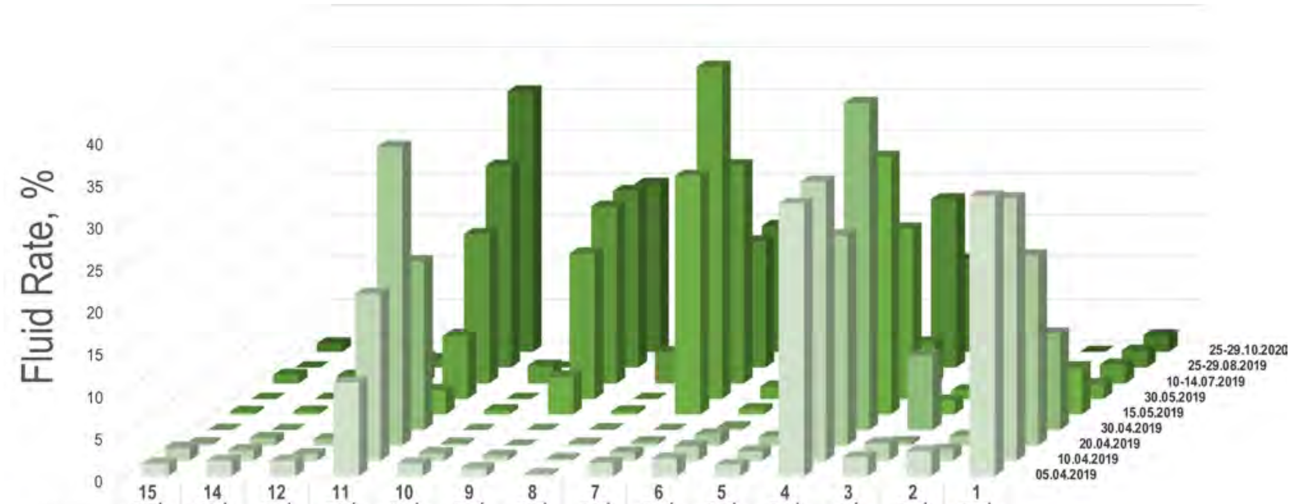


Figure 12—Geometry of the hydraulic fracture and proppant placement for stages 1-15

MSHF field operations were conducted on a regular basis. The well was put into operation by the free-flow production method. At the initial production stages, the well flow rates were maintained by an adjustable choke-flow bean. In July 2019, the well was switched to a mechanized method of operation. The results of continuous monitoring of well inflows are shown in Figure 13.



	15 port	14 port	12 port	11 port	10 port	9 port	8 port	7 port	6 port	5 port	4 port	3 ort	2 port	1 port
05.04.2019	2	2	2	11	2	1	0	2	2	1	32	2	3	33
10.04.2019	2	1	1	20	1	1	0	1	2	1	33	2	1	31
20.04.2019	0	1	1	35	0	0	0	0	1	1	25	0	1	23
30.04.2019	0	0	3	20	0	0	0	0	0	11	39	9	0	11
15.05.2019	0	0	1	3	0	4	0	28	1	1	31	2	1	5
30.05.2019	0	0	0	7	0	17	0	39	1	1	20	1	1	2
10-14.07.2019	1	1	3	18	2	21	4	26	1	3	5	0	0	2
25-29.08.2019	0	0	1	24	0	21	0	15	0	0	20	0	0	2
25-29.10.2020	1	0	2	31	4	20	2	15	3	1	11	2	0	2

Figure 13—Dynamics of the MSHF ports of the 113G well

The flow profile of the well under consideration is also uneven over the course of the study. For the first month of the study, the largest contribution of ports 1, 4, and 11 was observed. According to the well profile, ports 1-4 are located at the lowest absolute levels. Starting from the second month, ports 7 and 9 have been included in the well operation. Interestingly that during long-term monitoring, the profile shows an alternation of ports involved in the operation with almost non-operating ones, which indicates the probability of some competition between the formed fractures in the production of the target facility under study.

There is a decrease in the water cut of the reservoir fluid, which is probably also associated with fracturing fluid flow back. A similar pattern is typical for most wells in which operations are performed under selective stimulation of the reservoir. Initially, immediately after the starting, a high percentage of water (technical fluid) is observed, as the well is flown back and with a gradual and prolonged transition to the established filtration mode, the gel and other impurities pumped with proppant into the reservoir are washed out. Thus, this process can take quite a long time, and eventually all the water component is washed out.

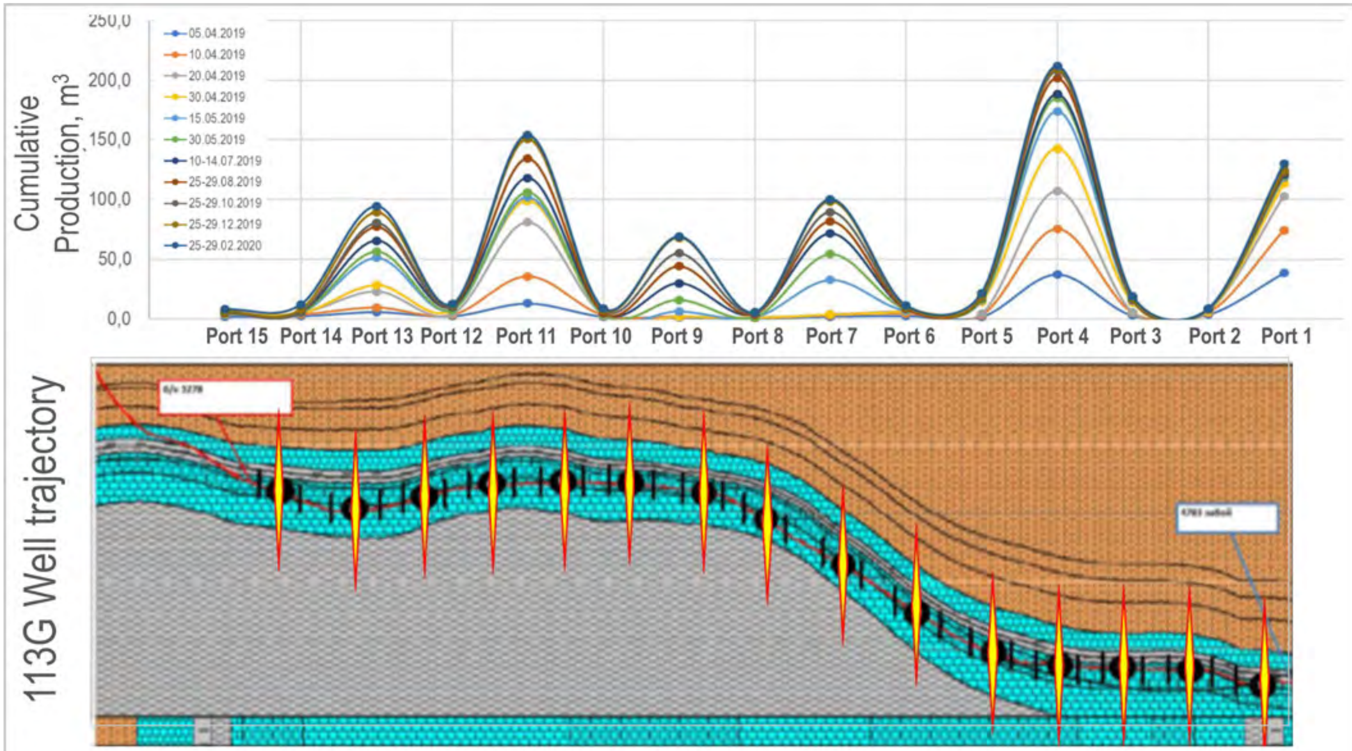


Figure 14—Distribution of the inflow profile based on the results of marker studies at the 113G well

Another horizontal well No. 113-1G located at the same site was also selected as a candidate for marker diagnostics. A 9-stage MSHF was performed in it.

All stages of MSHF were performed in the target treatment zone. The Customer agreed to conduct the MSHF operation summarized in Table 5. Figure 15 shows data on the flow, concentration, and supply of propane. Marked proppant is served at the penultimate stage, followed by the flush by usual ceramic proppant of the 20/40 fraction weighing 2 t.

Table 5—MSHF implementation Plan

Stage No.	Flow, m^3 / min	V_{fluid}, m^3	$Proppant_{Mass}$, t	20/40	20/40 (marked)	Supply, concentration kg / m^3
1–15	8	1,430	90	75	15	200

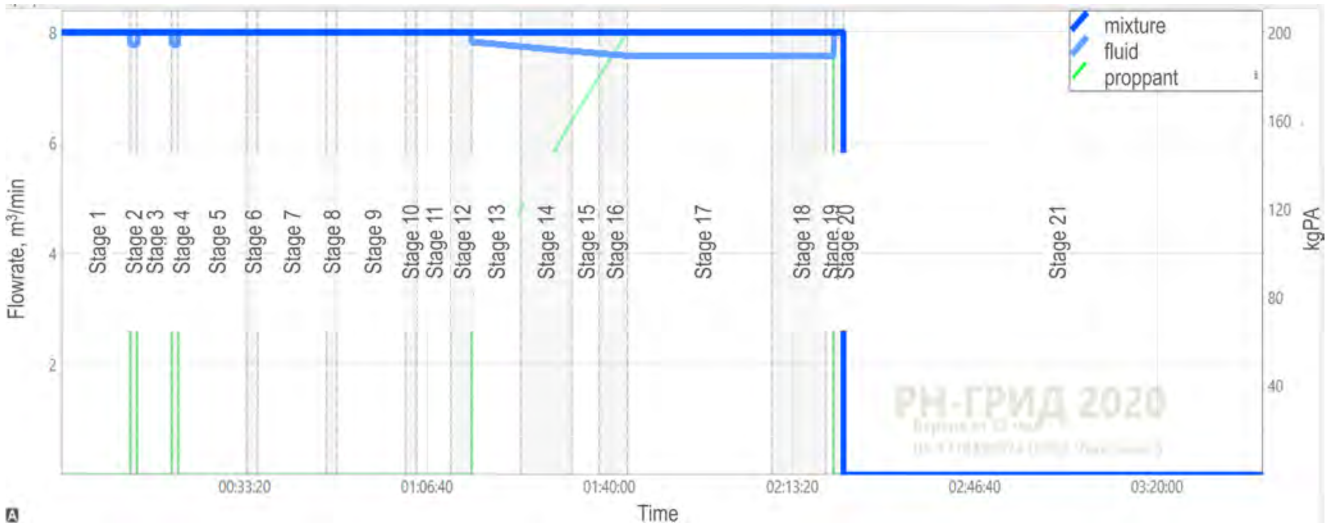


Figure 15—Hydraulic fracturing operation plan for stages 1-9

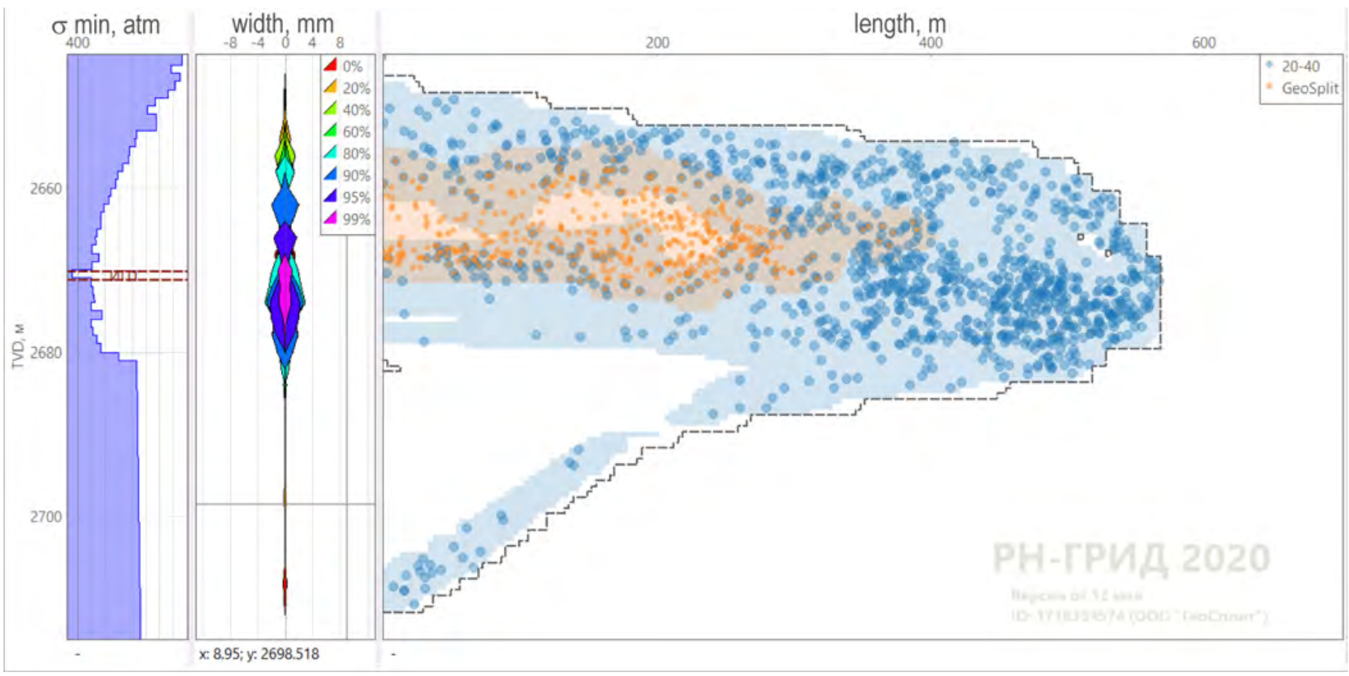
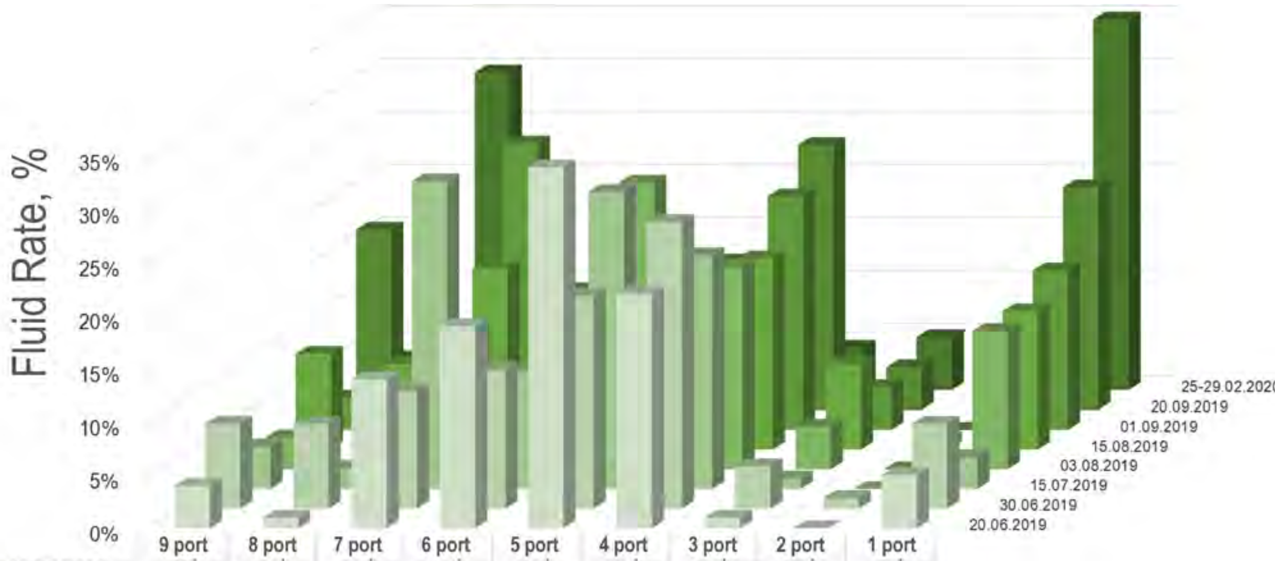


Figure 16—Geometry of the hydraulic fracture and proppant placement for stages 1-9

MSHF field operations were conducted on a regular basis. The well was put into operation by the free-flow production method. Maintenance of the flow rate at starting was performed by an adjustable wellhead choke, then after a short-term flow back operation, production was performed with the help of an ECP. The results of continuous monitoring of well inflows are shown in Figure 17.



	9 port	8 port	7 port	6 port	5 port	4 port	3 port	2 port	1 port
20.06.2019	4%	1%	14%	19%	34%	22%	1%	0%	5%
30.06.2019	8%	8%	11%	13%	20%	27%	4%	1%	8%
15.07.2019	4%	2%	29%	11%	28%	22%	1%	0%	3%
03.08.2019	3%	7%	13%	14%	27%	19%	4%	0%	13%
15.08.2019	9%	8%	17%	15%	11%	18%	8%	1%	13%
01.09.2019	3%	7%	27%	10%	12%	22%	4%	0%	15%
20.09.2019	17%	5%	11%	3%	14%	25%	4%	0%	21%
25-29.02.2020	3%	30%	3%	6%	11%	4%	5%	1%	37%

Figure 17—Dynamics of the MSHF ports of the 113-1G well

The well flow profile is uneven in the course of the study, and the central part (ports 4, 5, 6, and 7) makes the greatest contribution to the well operation. In February 2020, there is an active inclusion of the well ports 1 and 8 in the operation. Also, there is a decrease in the water cut of the reservoir fluid due to the gradual flow back of fracturing fluid after the well is put into operation.

It is also noted that during monitoring, ports 2 and 3 are almost not included in the operation (Figure 18). A possible reason for the low inflow is that the intervals reveal a zone with poor filtration properties or are located in a quite non-drained area.

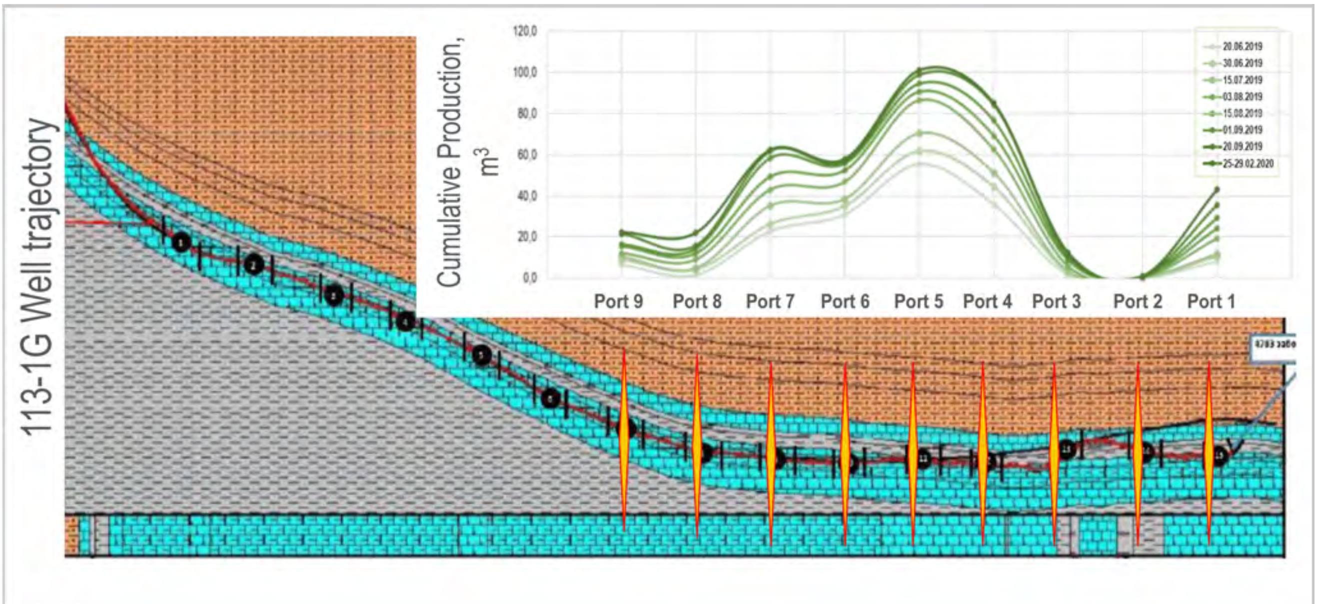


Figure 18—Distribution of the inflow profile based on the results of marker studies at the 115G well

CONCLUSION

The inflow profiles were monitored continuously for several months (from 2 to 10 months) using marked proppant from 113G, 113-1G, and 115G wells considered in the current operation. Based on the obtained analytical data, a quantitative assessment of the port operation was performed in the course of the study, which allowed for a long-term analysis of the stimulation efficiency for each of the hydraulic fracturing stages at each well under study. The revealed unevenness of the intervals production at each of the wells under consideration may be mainly due to the strong heterogeneity (according to reservoir properties) of the facility under study, as well as the formation of complex geometry of initiated fractures, as evidenced by the results of modeling on a specialized simulator. A pattern of decreasing productivity of ports located mainly in the "heel" part of the horizontal well was also revealed. There is reason to believe that as the production is developed, the mechanical skin factor gradually increases over time due to the man-made fractures clogging during production, which is partially displayed on the inflow profile.

In contrast to traditional research methods in horizontal wells, the technology for monitoring the inflow profile using marked proppant did not require the use of special means for delivering devices, was not subject to the risks of equipment sticking and ambiguity in the interpretation of the results, as well as did not require forced outage for round-trip operations.

A promising direction for applying the results of this work may be estimation of the production of reserves in the reservoir area, based on the accumulated average daily production for all areas in the study area.

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