Chair of Drilling and Completion Engineering

Master's Thesis

Selection of Technologies for Multilateral Wells' Completion in the Achimov Formations of Yamburg Field

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This Master's thesis dedicated to my family, my Father and Mother who put a lot of effort to help me find my path in life and allow me to pursue my education.

AFFIDAVIT

I declare on oath that I wrote this thesis independently, did not use other than the specified sources and aids, and did not otherwise use any unauthorized aids.

I declare that I have read, understood, and complied with the guidelines of the senate of the Montanuniversität Leoben for "Good Scientific Practice".

Furthermore, I declare that the electronic and printed version of the submitted thesis are identical, both, formally and with regard to content.

Date 01.07.2020 Shamkhal Mammadov

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Abstract

Today Western part of Siberia is still one of the leading oil and gas basins of Russia. However, the deficiency of perspective resources in maturated reservoirs and traps leads to an intense search of new perspectives in non-anticlinal traps. From this point of view, investigating Achimov's low-permeability sediments in the Yamburg oil-gas condensate field is necessarily crucial for maintaining production oil capacity on the required level.

It is essential to consider the main issues and questioned areas connected with Achimov formation and recognize its fundamental problems and uncertainties in all aspects of studying to make optimal drilling, completion, and exploration programs for the economically successful development of the reservoirs.

This Master thesis will cover the geological composition of the Yamburg field with a focus on the ranking system known as **T**echnology **A**dvancement of **M**ulti-**L**aterals (TAML), advantages and disadvantages of using various levels of TAML for completion in this geology and the frequent problems faced during well completion stage in the Yamburg field, like Achimov oil and gas formations and Valangin gas deposits and the problems faced in those intervals.

Also, a detailed review of multilateral wells construction and completion practices will be carried out for the selection of a possible solution for the Yamburg field. Drilling multilateral wells can be a promising application for the Yamburg field due to the presence of complex geology because this technology reduces enclosed expenses and the number of wells being drilled in the complex formations.

Master thesis work will result in the selection of completion technology and solutions for the complex geological structure of Achimov formation concerning the TAML methodology.

Zusammenfassung

Der westliche Teil Sibiriens ist bis heute eines der führenden Öl- und Gasbecken Russlands. Der Mängel an perspektivischen Ressourcen in ausgereiften Reservoirs und Fallen führt jedoch zu einer intensiven Suche nach neuen Perspektiven in nicht-antiklinalen Fallen. Unter diesem Gesichtspunkt ist die Untersuchung von Achimows Sedimenten mit geringer Permeabilität im Öl-Gas-Kondensat Feld von Jamburg unbedingt erforderlich, um die Produktionsvolumen auf dem erforderlichen Niveau zu halten.

Es ist wichtig, die Hauptprobleme und Fragestellungen im Zusammenhang mit der Bildung von Achimow zu berücksichtigen und ihre grundlegenden Probleme und Unsicherheiten in allen Aspekten des Studiums zu erkennen, um optimale Bohr-, Komplettierung- und Explorationsprogramme für die wirtschaftlich erfolgreiche Entwicklung der Stauseen zu erstellen.

Diese Master Thesis befasst sich mit der geologischen Zusammensetzung des Jamburg Feldes mit einem Schwerpunkt auf dem als TAML (Technology Avancement of Multi-Laterals) bekannten Ranking-System, den Vor- und Nachteilen der Verwendung verschiedener TAML-Ebenen zur Vervollständigung in dieser Geologie und den häufigen Problemen während der Bohrlochs Komplettierung auf dem Gebiet von Jamburg, wie Achimow-Öl- und Gasformationen und Valangin-Gasvorkommen, und die Probleme, mit denen diese Intervalle konfrontiert waren.

Außerdem, wird eine detaillierte Überprüfung der Bau- und Komplettierungspraktiken für multilaterale Sonden durchgeführt, um eine mögliche Lösung für das Gebiet von Jamburg auszuwählen. Das Bohren multilateraler Sonden kann aufgrund des Vorhandenseins komplexer Geologie eine vielversprechende Anwendung für das Gebiet von Jamburg sein, da diese Technologie die eingeschlossenen Kosten und die Anzahl der Sonden in den komplexen Formationen reduziert

Die Master Thesis wird zur Auswahl der Komplettierungstechnologie und der Lösungen für die komplexe geologische Struktur der Achimov-Formation in Bezug auf die TAML-Methodik führen.

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Table of Contents

1. Introduction

Yamburg Oil Gas Condensate field (YOGC) will become one of the biggest projects of Gazprom Neft's projects in the Siberia and the point of the company's further development, where Gazprom Neft has been actively producing in recent years.

The YOGC field was founded in 1969. In terms of gas reserves, it is considered as one of the largest in the world (where initially explored assets - 6.9 trillion cubic meters of gas). Gas production here has been started in 1986 and maintained until today, in 2018, YOGC field has produced about 65 billion cubic meters of gas. The majority of the oil assets deposited in the Achimov's formations of the field, which are structurally deep and complex. According to the Gazprom Neft's experts, the fluid reserves of the YOGC field can reach up to 3.5 billion tons, which means it can be included in the top twenty largest oil fields in the world. Achimov deposits have been known to geologists for decades, the first phases of exploratory works have been accomplished in 1999 by Rosgeologiya, while the experimental/pilot project started only in 2014, then, unfortunately, it did not reach the oil field development stage (Alekseev 2019).

The main task for today in the YOGC field is to select the right techniques and technologies for the effective recovery of these reserves. A lot of completion operations with large-volume hydraulic fracturing were tested in the fields of Western Siberia, which showed promising results. In 2020, it was planned to drill a multilateral well with two parallel wellbores in the Achimov deposits of the YOGC field with the application of a multi-stage hydraulic fracking method.

1.1 Thesis objectives

The key objective of this Master thesis is to prepare completion solutions for multilateral well with the selection of completion technology in the given geological conditions of Achimov deposits.

The results of this study may not only help in the implementation of the Yamburg X project but could also become a common solution for West Siberia fields' development.

Sub-objectives:

1. Provide well trajectory using Landmark Compass software considering both pressures and lithology and analyze drilling possibility;
2. Provide well schematic design using Landmark Casing Seat and Landmark Stress Check software;
3. Selection of technology for completion of a multilateral well considering the future requirements for increasing well inflow performance by the implementation of multi-stage hydraulic fracturing;
4. Analyze the possibility to use an intelligent well completion solution that will allow efficient monitoring of the wellbore conditions, which enables the collection, transmission, and analysis of well and reservoir data. The smart

completion architecture should enable actions to manage changes in well downhole conditions and regulate the inflow.

5. Develop an improved well completion solution and casing design for the multilateral well, taking into account experience of the previous well, defining the milling depth for the lateral wellbore, and selection of completion technology according to the requirements from the customer.

1.2 Industrial advisors and their inputs

1.2.1 Gazprom Neft "Science & Technology Center"

Gazprom Neft STC Science and Technology Center was established in October 2007. The STC employs more than one thousand scientific staff. The main objectives of Gazprom Neft STC are the designing, analyzing, and monitoring of oil field development and exploration, geological and hydrodynamic modeling, technological support, and operational control of drilling. The area of responsibility of the STC includes: creating and maintaining a corporate base of geological and field information, managing the process of extracting oil from the formation, planning, and organizing industrial pilot works on the introduction of advanced technologies in oil production. Gazprom Neft STC is Russia's only facility that collocates scientific research, development of oil production technologies, and remote management of high-tech operation processes (Gazprom Neft STC n.d.).

The Following data was given by Gazprom Neft (Science and Technology Center) specialists to achieve the aforementioned objectives.

- Drilling and completion program of the subject well;
- Geology and lithology for of the Yamburg field;
- Rig and equipment information;
- Yamburg Project model;
- Field Development strategy;
- The technological session for field development

1.2.2 "NewTech services"

NewTech Services is an international service company providing high-tech solutions since 2009. NewTech Services operates in Russia, USA, UK, Serbia, Azerbaijan, Ukraine, Kazakhstan, Belarus, Romania, Saudi Arabia, Argentina. The company has professional experience in the petroleum industry, NewTech Services, and capable of understanding customers' objectives to achieve the best results at a minimal cost.

The Following data was given by NewTech Services' specialists to achieve the aforementioned objectives.

- Description of modern completion technologies.
- Technologies for carrying out MSHF
- Design for Multilateral wells completion

1.3 Field development strategy

The new company strategy of Gazprom Neft allows to investing its funds in geological exploration, technological improvement, and infrastructure operations, considering all geological and operational risks, which at the same time allowed to develop Achimov deposits of YOGC field that were not profitable before. The productivity re-evaluation of the Achimov oil deposits of the YOGC field Gazprom Neft continued in 2017. In the same year, investments for re-testing of exploration wells of the field were approved. In 2018, for the first time, Gazprom Neft has carried out a large number of hydraulic fracking operations with the volume of pumped proppant of 500 tons, which allowed obtaining industrial inflows from low-permeable Achimov deposits. The actual production rate for one of the wells was more than twice than expected. Then in March 2019, the first two horizontal wells were drilled, and multi-stage hydraulic fracturing operations were carried out. Experimental and industrial practices made it possible to select the optimal well construction design, reduce the drilling cost, and maximize the production rate. The results obtained during the drilling and completion of these wells acknowledged the company to decide in which form and speed the project should be implemented, as well as to define a further field development program. The project will allow development technology and strategy, which will later be used in the exploration of previously uneconomical oil reserves of Achimov deposits in the other fields of West Siberia (Gazprom Neft n.d.).

1.4 The challenge of Achimov formations

The main challenges that the petroleum engineers encounter during in the Achimov formations are low reservoir properties and poor reservoir connectivity. At depths of 3200–4000 m, where the Achimov deposits occur, the rocks are described by an alternation of fine-grained sandstones, siltstones with mudstones, which have a permeability of no more than 3 mD and often below 1 mD. For comparison, Neocomian strata in these deposits formed by medium and coarse-grained sandstones have a permeability of almost seven times higher: up to 20 mD. Besides, the formations are often highly clayed and carbonized, which makes it difficult to interpret the data from the geophysical logs. It is not surprising that in the 80s in the wells during trial operation, they received low production rates and accumulated production per well. Considering that a complex structure also characterizes the group of Achimov layers, the further development of these strata using the technologies available at that time was considered inappropriate. Even though the records of the Achimov deposits geological studies are several decades old, the volume of reserves development in these deposits does not even reach 10%. The number of licensed objects at which the Achimov deposits are put into commercial development is few.

1.5 Chapter summary

Achimov deposits of the YOGC field have a huge resource potential, and its reserves can make up to 40% of the total resources of Gazprom Neft. These deposits are extremely complex in terms of geology, which requires the use of innovative technologies. If the task of conventional geology is to find the location of deposits, when working with unconventional reserves, the main thing is to select the tools of their development accurately. In the case of Achimov deposits, it is necessary to do both: to correctly find and cost-effectively extract reserves, having chosen technologies taking into account numerous challenges, as abnormal pressures, and low permeability reservoir formations.

2. Field data review and analysis

In this chapter field data of the YOGC field will be reviewed in detail, field geology and drilling program of the first experimental horizontal well will be described together with possible complications and hazards.

2.1 YOGC field overview

The YOGC field was discovered in 1969, it is in the Polar part of the West Siberian Plain, on the Taz Peninsula in the subarctic zone of the Yamalo-Nenets Autonomous District of the Russian. Yamburg field is located 330 km northeast of the Salekhard city and is confined to the Yamburg and Harvut raises of the Urengoy oil and gas region of the West Siberian oil and gas province. The map of the Western Siberia and YOGC field is shown in Figure 1.

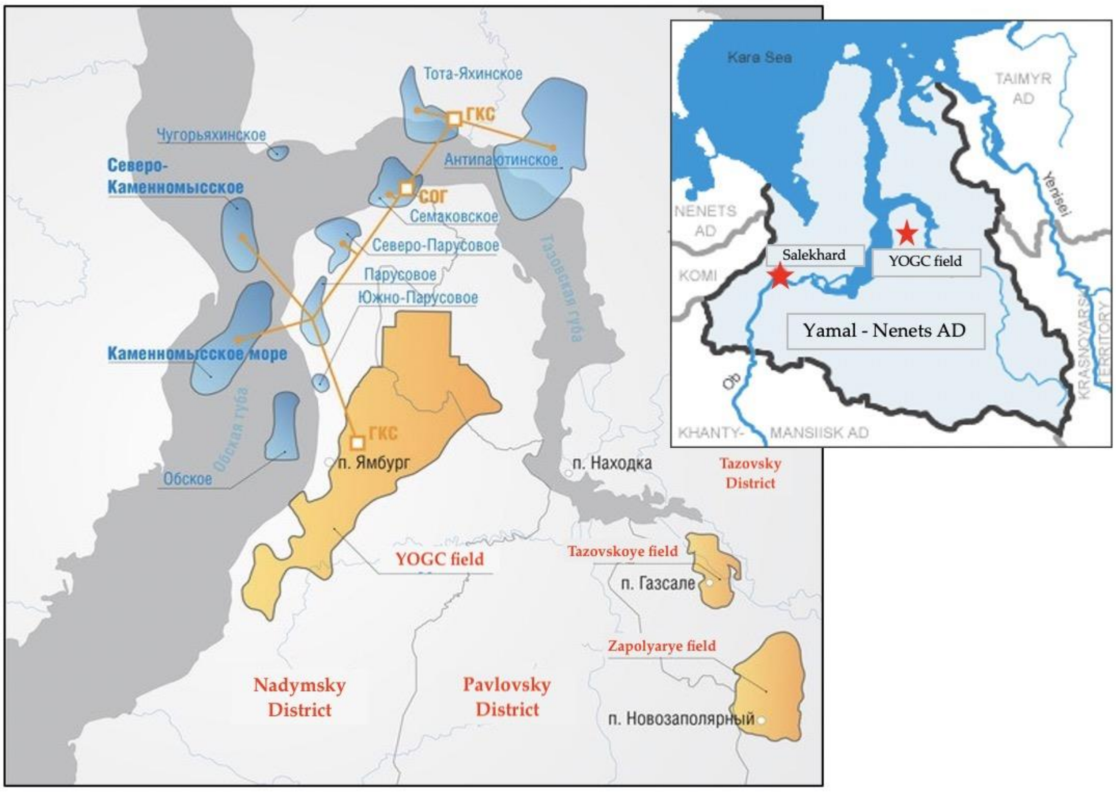

Figure 1: YOGC field map

Geology of the Yamburg oil and gas condensate field is represented by sandy-clay deposits of the Mesozoic-Cenozoic platform cover, which overlays the rocks of the Paleozoic folded basement. In tectonic terms, the Yamburgskoye field is confined to the large Yamburgskoye mega-swell, elongated in a northeast direction. Industrial oil and gas potential is associated with such oil and gas complexes as Lower-Middle Jurassic and Neocomian. The industrial gas content of the Yamburg field is associated with the Cenomanian and Valanginian deposits. The dimensions of the Cenomanian area are 170x50 km, the gas zone height is 220 m, at the following depth intervals 1000-1700 m. The deposits are vaulted and massive, with open reservoir porosity up to 30%, with dry gas and methane (CH_4 – 93.4-99.2%). In the Lower Valanginian-Barremian deposits, the gas content of 19 productive formations was established, which are represented by the alternation of sandstones, siltstones, and mudstones. The gas contains about 90% methane, as well as nitrogen and carbon dioxide. Formations also include minor oil deposits. During the operation of the YOGC field, more than 4 trillion cubic meters of gas and about 18 million tons of gas condensate were produced. Gas preparation for transportation is carried out at 5 gas pre-treatment plants and 9 gas treatment plants. Estimated residual hydrocarbons in place are shown in Figure 2.

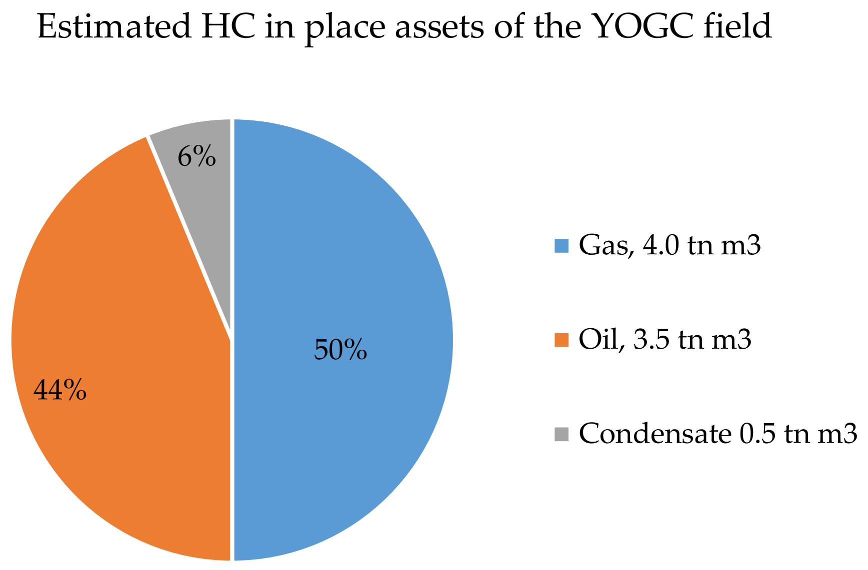

Figure 2: Estimated residual assets of the YOGC field.

Oil deposits of Yamburg field mostly concentrated in Achimov deposits and are located below the Cenomanian deposits. The productive complex was formed over a long geological history related to the accumulation and subsequent change in precipitation, the formation, and growth of traps that led to the creation of oil and gas collectors and Achimov deposits were a typical example of that. The liquid hydrocarbon reserves of the Yamburgskoye field are estimated at 3.5 billion tons, which makes it unique in terms of oil reserves. The oil and gas potential of the Achimov deposits of the field was established in 1999. In 2018, Gazprom Neft has conducted a large number of hydraulic fracturing operations at 2 wells with a proppant volume of 500 tons pumped. The actual flow rate of one of the wells from Achimov formations was almost two times higher than the target. Gazprom commercial oil production of the Achimov deposits at the YOGC field is planned for 2024. The production volume up to 8 million tons of oil equivalent per year is expected. The decision on the route for the delivery of oil from the field will be made in 2020:

- it can be either exported by oil tankers with the installation of an oil terminal
- or by connection to the main Arctic oil pipeline – Purpa Transneft, which located to the East from this field.

Achimov deposits occur in the interval between 3200 - 4000 m and have a much more complex geological structure than the aforementioned deposits. Sandstones and sandy siltstones in the formations are present mainly in the eastern part, in the paleoslope zone.

In the western part of deposits, towards to the deep-water section of paleobasin development, the thickness of the layers decreases sharply due to the disappearance of sand and siltstone interlayers from the section. In the direction from north to west, the Achimov deposits are caused by problem geological clinoforms, the structure, and distribution of which should be taken into account at the stage of well development. Taking into account the structure of the clinoform model in Neocomian sediments, it can be said that the formation of the Achimov deposits occurred by moving sand – silty sediments in the form of landslides and muddy streams from the shallow water zone to deep-sea conditions. In the Achimov deposits, several local clay reference layers with thickness from 3m up to 15m are distinguished. These interlayers divide the Achimov formation into several independent layers. Achimov formations are reservoirs with a very complex distribution of lenticular bodies – collectors. Achimov deposits have abnormally high reservoir pressures (more than 60 Mpa) and are complicated by tectonic and lithological barriers, characterized by the multiphase state of the deposits. The production costs of the Achimov oil and gas fluids surpass the cost of the Cenomanian's, whose reserves are in the final exploration phase, therefore, the development of the Achimov deposits is important to extend the exploitation process of the field. The development of hard-to-reach Achimov deposits will make it possible to extract additional volumes of hydrocarbons in the fields with decreasing production.

2.1.1 Abnormal pressures and anomaly coefficient

Achimov formation has several challenges, one of them being High pressure and High temperature (HPHT). During the past years, there was a lot of misunderstanding between service companies and institutions for defining HPHT formations and wells. Due to this problem, in 2012, the American Petroleum Institute (API) proposed the designation of HPHT and its classification. According to this, wells and formations were classified based on temperature and pressure changes, with consideration of equipment specification and accepted materials for HPHT conditions. Figure 3 shows the classification of HPHT conditions proposed by API (Smithson 2016).

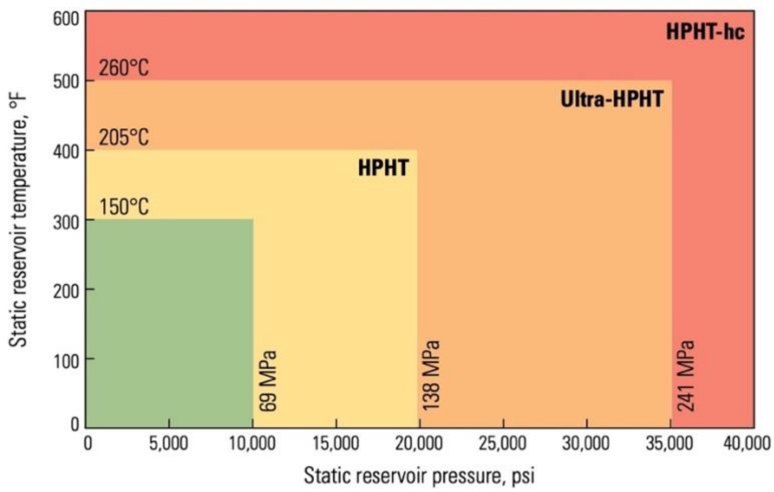

Figure 3: HPHT classification proposed by API in 2012

In Russian literature, this term defined as wells and formations with abnormal pressures or anomaly coefficient, which we going to consider in this chapter. Formation pressure is the pressure acting on the fluids in the porous space of the formation. Normal formation pressure in any geological conditions equal to hydrostatic formation of the fluid column from a surface to the formation. Therefore, according to such definition formation pressures characterized by any deviations from the normal change of pressure are abnormal pressures. Normal change of formation pressure is considered as 0,01 Mpa/m. Formation pressure exceeding hydrostatic pressure in specific geological conditions is defined as abnormally high formation pressures or overpressure zones. Whereas formation pressures less than hydrostatic are called abnormally low formation pressures or subnormal pressures zones. Even after decades of studies the origin of abnormal pressure not fully discovered yet, but the main reasons for them to occur are the following:

- consolidation of clay breeds,
- osmosis processes,
- processes of the catagenetic transformation of rocks and organic matter contained therein,
- processes of a tectogenesis,
- geothermal conditions of Earth 's subsoil,
- the temperature factor, the coefficient of thermal expansion of fluids enclosed in the isolated volume of rocks, is considerably higher than that of mineral components of rocks.

Abnormally formation pressures are established by drilling numerous wells onshore and offshore during the search, exploration, and development of oil and gas deposits in various reservoirs all around the world. Besides making the well drilling process more complex abnormal pressure has positive sides too. For instance, abnormally high pressure may:

- increase the permeability of rocks – collectors,
- increases the time of natural exploitation of oil and gas wells without the use of secondary methods,
- increases specific gas reserves and well production rate,
- is being favorable concerning the safety of hydrocarbon accumulations,
- indicates the presence of isolated areas and zones in oil and gas-bearing basins.

The pressure anomaly of formation is being defined by the anomaly coefficient K_a. This coefficient defined as a ratio of pore pressure at a certain depth to the hydrostatic pressure of fluid column at the same depth:

$$K_a = \frac{P_p}{\rho_f \cdot g \cdot h_f} \quad (1)$$

Where: K_a – anomaly coefficient; P_p – pore pressure of the formation; ρ_f –density of fluid; g – acceleration to gravity; and h_f –depth of the fluid.

Formation pressure is considered abnormal when the anomaly coefficient of the formation is more than 1,1 or less than 0,9 (Neftegaz.RU 2017).

2.2 Lithology and stratigraphy of the field

Lithology and Stratigraphy of the YOGC field are presented below in Tables 1 and 2.

Table 1: Stratigraphical well profile and cavernosity ratio

Occurrence depth, (m)		Stratigraphic division		Bedding elements		Cavernosity ratio
Top	Bottom	Naming	Index	Angle	Azimuth	
0	105	quarternary deposits	Q	0°	B-90	1.5
105	255	Atlimskaya + Novomikhailovskaya	P2 Atl + nm	0°	B-90	-
255	330	Lyulinvorskaya	P2 LL	0°	B-90	-
330	535	Tibeysalinskaya	P1 tbs	0°	B-90	-
535	750	Gankinskaya	K2 gn	0°	B-90	1.2
750	1070	Berezovskaya	K2 br	0°	B-90	-
1070	1130	Kuznetsovskaya	K2 kz	0°	B-90	-
1130	2210	Pokurskaya	K1-pk	0°	B-90	1.15
2210	3252	Tangalovskaya	K1 tn	0°	B-90	-
3252	3965	Sortimskaya	K1 sr	0°	B-90	-
3965	4032	Bazhenovskaya	J3 bg	0°	B-90	1.1

Table 2: Lithological well profile.

Stratigraphic Index	Occurrence depth, (m)		Rock name, type, and description.
	Top	Bottom	
Q	0	105	Peat, loams, sands, frozen rocks, clays.
P2 Atl + nm	105	255	Sands, loam, aleurites, aleurites clays.
P2 LL	255	330	Diatomaceous and aleurites clays. Bright-grey diatomites with slightly clay content. Flasks and flasky sands with blue-grey tints
P1 tbs	330	535	Grey sands, with yellow-grey aleurites clay interlayers. Grey clays with dark grey sands interlayer at the top.
K2 gn	535	750	Grey clays with greenish tint with limy aleurites clay interlayers.
K2 br	750	1070	Slightly aleurites, dark-grey clays with flasky aleurites and flasks interlayers.

Stratigraphic Index	Occurrence depth, (m)		Rock name, type, and description.
	Top	bottom	
K2 kz	1070	1130	Viscous and micaceous dark grey clays
K1-pk	1130	2210	Alternation of sandstones, aleurites, and clays with coal interlayers
K1 tn	2210	3252	Layers of sandstones, aleurites, and argillites
K1 sr	3252	3965	Argillites with sandstone interlayers in top
J3 bg	3965	4032	Black argillites, bituminous, with clay-limestones interlayers

2.3 Possible well complications

Drilling complication – is a disturbance of the planned drilling program, which interrupts the normal progress of the well construction and as consequence results in delays in the project. Section 2.3 is dedicated to possible well complications which could arise during the drilling and completion process of well construction in the Yamburg field, they considered from the complex geological point of view and analysis of 2 offset wells. The following complications could happen during the operations:

- drilling mud losses (loss of circulation);
- caving and collapses of wellbore walls;
- wellbore influx intervals;
- pipe sticking intervals;
- wellbore narrowing.

2.3.1 Drilling mud losses (loss of circulation)

Due to complex geology known from the Yamburg and offset wells analysis, the following fluid losses considered in the drilling operations and presented below in Table 3.

Table 3: Intervals with potential fluid losses

Stratigraphic Index interval	TVD, (m)		Maximum fluid loss rate m^3/h
	Top	Bottom	
Q – P1 tbs	0	535	up to 3
K2 gn – K1 pk	535	1203	up to 5
K1 pk	1203	2210	up to 5
K1 tn	2210	3252	up to 5
K1 sr	3252	3965	up to 5

Possible reasons for complications are:

- deviations in drilling program;
- speeding up during RIH/POOH (tripping) operations;

- violation of drilling mud properties, like viscosity, density, water loss.

2.3.2 Cavings and collapses

Table 4: Intervals with potential cavings and borehole wall collapses

Stratigraphic Index interval	TVD, (m)		Rock stability till beginning (days)	Intensity of forming	reaming due to complications	
	Top	Bottom			interval	Speed m/h
Q – P1 tbs	0	535	3	intensive	535	100-120
K2 gn – K1 pk	535	1203	3	weak	668	10-20
K1 pk	1203	2210	3	weak	1007	10-20
K1 tn	2210	3252	3	weak	1042	10-20
K1 sr	3252	3965	3	weak	713	10-20

Possible reasons for complications:

- Violation of drilling technology;
- speeding up during RIH/POOH (tripping) operations;
- organizational downtime (repair work, waiting for tools, materials);
- non-observance of drilling fluid parameters, including density, water loss, viscosity;
- untimely reaction to signs of complications.

2.3.3 Wellbore Influx intervals – "kicks"

Kick occurs when the pressure in the formation is higher than the hydrostatic pressure of drilling mud. Since the Achimov deposits have many gas interlayers, there is a possibility that influx could happen during drilling, therefore, on the planning stage of development, appropriate well control measures are taken. Possible kick intervals presented below in Table 5

Table 5: Possible kick occurrence intervals.

Stratigraphic subdivision	TVD, (m)		Influx type
	Top	Bottom	
Ach_{14}^{3}	3234	3252	Gas/condensate, water
Ach_{15}^{1}	3259	3266	Gas/condensate
Ach_{15}^{2}	3277	3340	Gas/condensate
Ach_{15}^{3}	3606	3663	Gas/condensate
Ach_{17}^{1}	3691	3700	Gas/condensate
Ach_{17}^{2}	3700	3759	Gas/condensate

Stratigraphic subdivision	TVD, (m)		Influx type
	Top	Bottom	
Ach_{17}^{3}	3767	3865	oil
Ach_{18}^{1}	3869	3902	oil
Ach_{19}^{1}	3919	3932	Gas/condensate

Complications with the decrease of the hydrostatic pressure in the well could occur due to:

- lowering the level of the drilling fluid during drilling or shut-in fluids during testing during tool tripping and the absence of topping up the well;
- lifting the drill string in the presence of a siphon or swabbing – the requirements for elimination following the Safety Rules;
- the decrease in the density of the drilling fluid or fluids that fill the well below the assigned value determined following the Safety Rules.

2.3.4 Pipe sticking

The Stuck pipe – is the loss of the pipe string mobility due to sticking. In the experience of drilling the first well, the differential and mechanical sticking problems were observed.

Table 6: Stuck pipe potential

Stratigraphic Index interval	TVD, (m)		Repression while sticking, (Mpa)
	Top	Bottom	
K2 gn – K1 pk	535	1203	0.5
K1 pk	1203	2210	0.5
K1 tn	2210	3252	0.5
K1 sr	3252	3965	0.7

The Stuck pipe may occur in the drilling intervals mentioned in Table 6 under the following conditions:

- Deviation of the properties and parameters of the drilling fluid from the designed;
- poor bottom hole cleaning from the cutting;
- leaving the drilling string in the open hole without movement when drilling or tripping operations stopped;
- organizational stand by time.

2.4 Well profile and casing design of the well H-1

In this subchapter well profile and casing design of the first experimental horizontal well H-1 is described in detail. Compass and Well Plan software was used, to visualize well trajectory and casing design according to the drilling program provided by industrial partners.

During the well planning process and evaluation, following mining and geological characteristics of the West Siberian formations were taken into account:

- Permafrost rocks occur in the interval 0 – 500m;
- zero isotherm depth is 450 m;
- The rocks' temperature at a depth of 7m is - 6 ° C.
- ice content – up to 40%

Profile of the main borehole presented as a J-type well. Horizontal profile with 5 - intervals were selected. More precisely, the vertical section followed by build-up – hold – build-up intervals and concluded by tangential horizontal interval are distinguished in the project documentation.

Due to the presence of two zones with abnormally high pressures, it was accepted to block these zones with two additional liners. This five-column design eliminates all risks associated with well integrity. Mud window with upper and lower design constraints and casing setting depths is shown in Figure 4.

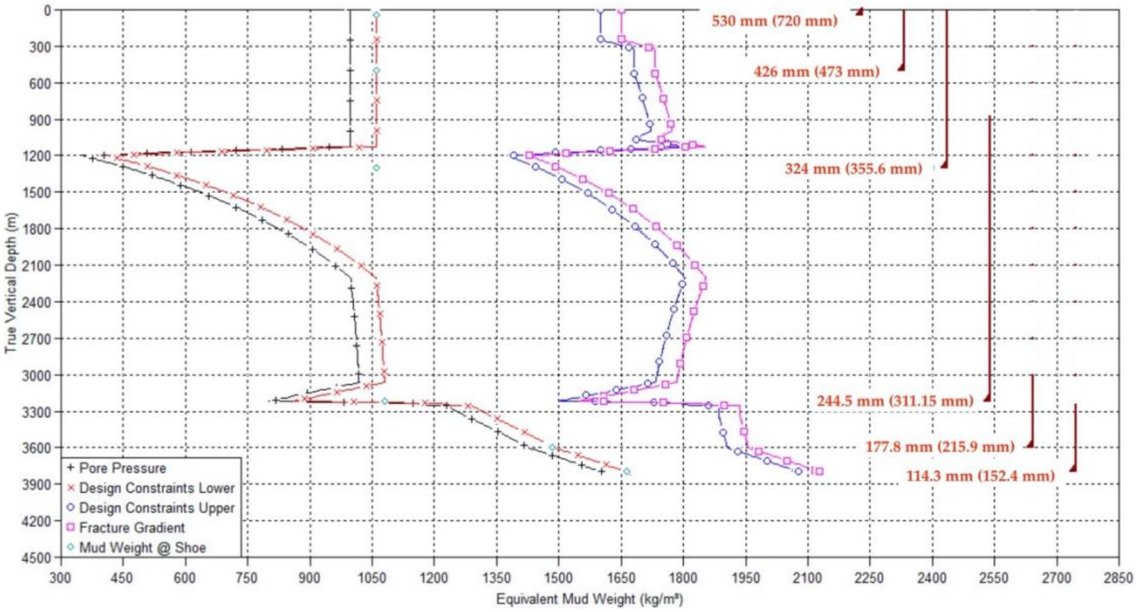

Figure 4: Mud window with safety constraints and casing depths.

After cementing 178 mm (7 in) liner, the pilot wellbore with the diameter of a bit 155.6 mm (6 1/8 in) was drilled to the TD of 3932 m, to carry out open-hole geophysical logging operations, collecting core samples and determine the target interval of the horizontal well. After logging and coring operation, the pilot wellbore was eliminated following the requirements of the safety regulations of Russia. The well trajectory in 3D is presented below in Figure 5.

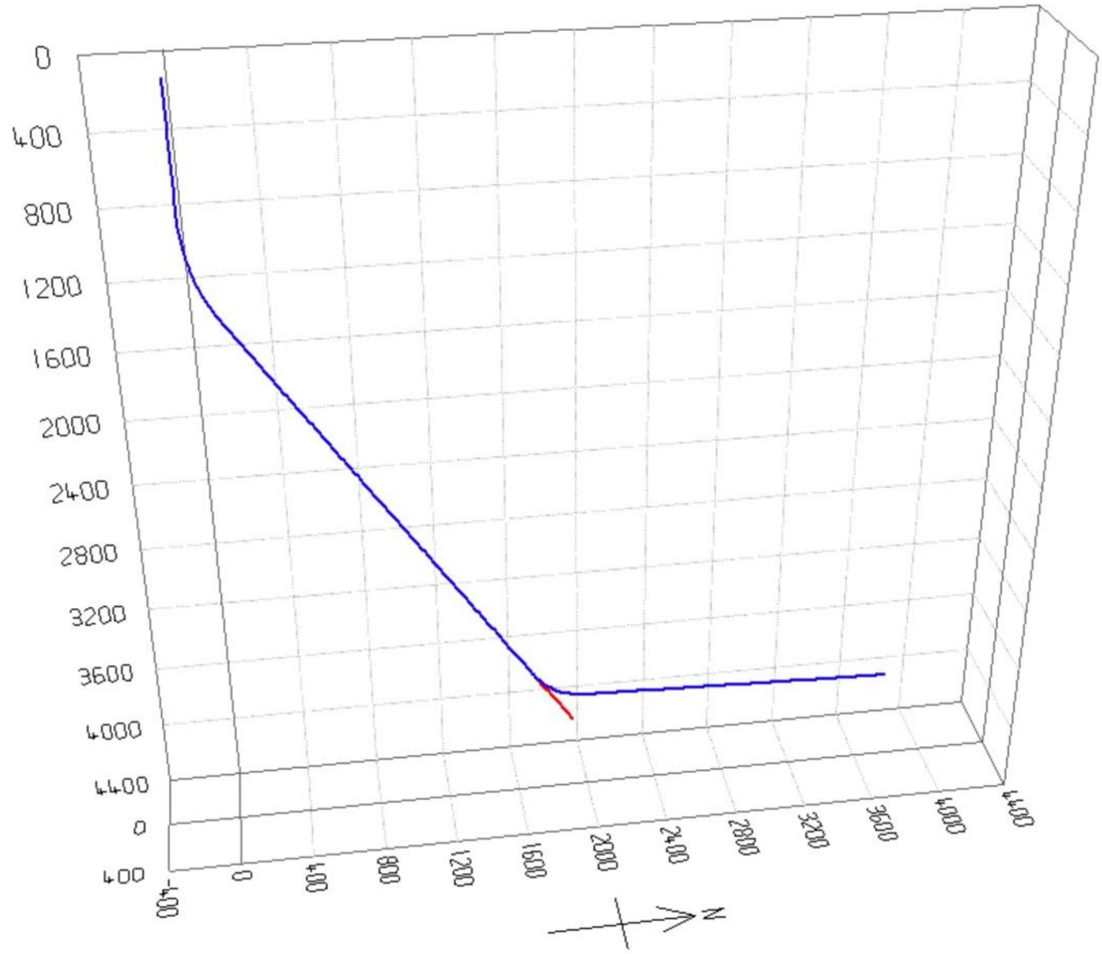

Figure 5: Well trajectory with pilot wellbore(red) in 3D.

2.5 Mud program

This subchapter is designed following the well construction instructions and Safety Regulations by the design assignments.

Conductor casing drilling is provided on polymer-clay solution from previously drilled wells. The solution will be treated with chemical reagents and parameters of drilling mud adjusted to design ones. Drilling of surface casing, first and second intermediate, and liners are provided by oil-based drilling mud from previously drilled wells. Presented on Table 7 drilling mud parameter used in drilling well H-1 will be adjusted to reach the designed parameter for drilling a multilateral well.

Table 7: Drilling mud types and parameters.

Mud type	MD, m	Density kg/m³	Funnel viscosity (c)	Filter cake thickness	Plastic viscosity mPa·c	Gel strength 10sec/10 min	Shear stress mPa·c	PH
Polymer-clay mud	0 - 50	1100 - 1140	60 – 90	1,0 – 1,5	18 - 25	9 – 15 13 – 21	25 – 30	8 – 9
Oil-based mud	50 - 300	1100 - 1140	60 – 90	1,0 – 1,5	18 - 25	9 – 15 13 – 21	25 – 30	8 – 9
	300 - 500	1100 - 1140	45 – 50	1,0 – 1,5	18 - 25	9 – 15 13 – 21	25 – 30	8 – 9
Oil-based mud	500 - 1315	1100 - 1140	25 – 30	0,5 – 1,0	12 - 20	2 – 6 4 – 11	15 – 20	8 – 9
Oil-based mud	1315 - 3581	1100 - 1140	30 – 35	0,5 – 1,0	40 - 50	4 – 9 5 – 11	15 – 25	8 - 3
	3581 - 3642	1400	30 – 35	0,5 – 1,0	40 - 50	4 – 9 5 – 11	15 – 25	8 - 3
Oil-based mud	3642 - 3720	1400 - 1700	30 – 35	0,5 – 1,0	40 - 50	4 – 9 5 – 11	15 – 17	9,5 – 3,7
	3720 - 4092	1700	50 - 70	0,5 – 1,0	40 - 50	4 – 9 5 – 11	15 – 17	9,5 – 3,7
Oil-based mud	4092 - 6200	1840	50 - 70	0,5	50 - 80	5 – 13 6 - 15	15 - 20	9,5 – 3,7

2.6 Drilling parameters and drill string components

The used components of the drill string in the drilled subject well H-1 and the applied drilling parameters are presented below in Tables 8 and 9.

Table 8: Drilling parameters of experimental well H-1

Intervals MD, m		Drilling method	Axial loads kN	Torque, N·m	Drill string rotating speed, RPM	Flow rate, L/m	Rate of penetration m/h
from	to						
0	50	rotary	10 - 30	1000	60 - 120	3331	15 - 20
50	500	rotary / PDM	20 - 100	2840	up to 40	3331	10 - 15
500	700	rotary / PDM	20 - 100	3330	up to 40	2972	15 - 20
700	1315	rotary / PDM	20 - 100	6140	up to 40	2972	15 - 20
1315	3642	rotary / PDM	20 - 100	19710	up to 40	2536	15 – 25
3642	4092	rotary + RSS	20 - 100	21828	100 - 130	1401	30 - 45
4092	6759.2	rotary + RSS	20 - 100	24403	100 - 150	850	30 – 45

Table 9: Drilling string components used in experimental well

Casings	№	Drilling strings components	Length, (m)	Distance from the bottom, (m)
Conductor 0 - 50	1	7′′ DC, 5,365 tons	18,12	18,22
	2	8′′ DC, 2,808 tons	30	48,12
	3	32 1/4′′ reamer	0,69	38,81
	4	8′′ sub	0,5	49,31
	5	26′′ bit	0,69	50
Surface 0 - 500	1	5′′ DP, 14,547 tons, M	439,81	439,82
	2	7′′ DC, 5,365 tons	18,12	457,94
	3	8′′ DC, 2,808 tons	30	487,94
	4	8′′ PDM	10,13	498,07
	5	19 1/2′′ stabilizer	1,3	499,37
	6	19 1/2′′ bit	0,63	500
1st intermediate 0 - 1336	1	5′′ DP, 42,247 tons, M	1277,29	1277,30
	2	7′′ DC, 5,365 tons	18,12	1295,42
	3	8′′ DC, 2,808 tons	30	1325,42
	4	8′′ PDM	10,13	1335,55
	5	15 1/2′′ bit	0,45	1336
	1	5′′ DP, 42,247 tons, M	1277,29	1277,30

Casings	№	Drilling strings components	Length, (m)	Distance from the bottom, (m)
Tie back Line 3642 - 4092	1	5′′ DP, 126,7 tons, S	3829,55	3829,55
	2	6 1/2′′ Hyd. jar	6,8	3836,35
	3	5′′ DP, 6,61 tons, S	200	4036,35
	4	7′′ DC, 2,8 tons	36	4072,35
	5	7 ′′ MWD/LWD	10,96	4083,32
	6	7 1/2′′ PDM	8,3	4091,62
	7	8 1/2′′ bit	0,38	4092
Liner 4092 - 6200	1	3 1/2′′ DP, 126,7 tons, S	4289.79	4289.79
	2	4 3/4′′ DC, 4,97 tons	80	4369,79
	3	643/4′′ Hyd. jar	5.5	4375,29
	4	3 1/2′′ DP, 38,32 tons, S	1805	6180,29
	5	4 1/2 ′′ MWD/LWD	12,34	6192,63
	6	5′′ PDM	7,08	6199,71
	7	6 1/8′′ bit	0,29	6200

3. Multilateral well construction

This chapter will discuss the Multilateral well construction and the difficulty levels of their completion, also problems affecting the selection criteria of the TAML level of completion in the Achimov deposits. An overview of the drilling cluster № 1_14 at the YOGC field will be made, in which the multilateral well with two wellbores located parallel to each other at the same vertical depth, instead of two normal horizontal wells, would be proposed.

3.1 History of multilateral wells

The development of drilling technologies and methods over the past hundred years has made it possible to create branched wells, also called multilateral wells. Multilateral wells are the wells with one or more additional branched wellbores from the main wellbore. It may be a conventional production, infill well, or lateral wells drilled from an existing well. Successful multilateral well substituting several "regular" wells can reduce the overall drilling and completion costs, increase productivity, and provide more efficient fluid flow from the formation. Moreover, the use of multilateral wells can provide more effective management for field development and increase oil recovery rates. The idea of multilateral drilling technology has a very enduring history. The first patent of the whipstock for the directional drilling technology was acquired in the United States in 1929 (Total EP 2016). In the Former Soviet Union (FSU), the development of directional drilling with turbodrill started from the late 1930s. First directional cluster drilling experience gained in the 40s in the Perm region. This led to the development of horizontal drilling and Multilateral well drilling technology (Y.A.Gelfgat 2003). Multilateral technology, the same as the other latest developments in the oil industry, was developed and successfully applied for the first time in the FSU in Bashkoristan in 1953 by Soviet drilling engineer A. M. Grigoryan (Bosworth 2016). During the Soviet Union era, official policy was directed at producing as much oil as possible. It was a strategic asset, and one of the few exported goods. High demands were placed on drilling companies to improve drilling technologies for the fast and efficient construction of as many wells as possible, which in turn increased oil production and made the USSR the leading oil producer by the 80s. (Y.A.Gelfgat 2003)

During 1950-1954 Alexander Grigoryan with his team was working on multilateral wells. Kartashev field in Bashkoristan with riff reservoir thickness from 100m to 300m was specially chosen to implement the drilling project of multilateral wells. The rock properties like density and hardness were ensured wellbore stability for a long period. During this period Ishimbaineft engineers built five multilateral wells, with a curvative radius up to 80m. The first three wells had three laterals, fourth well had seven laterals and the last well had 10 laterals. Figure 6 shows the fifth multilateral well with №66/45 drilled by Grigoryan in 1953 (Y.A.Gelfgat 2003).

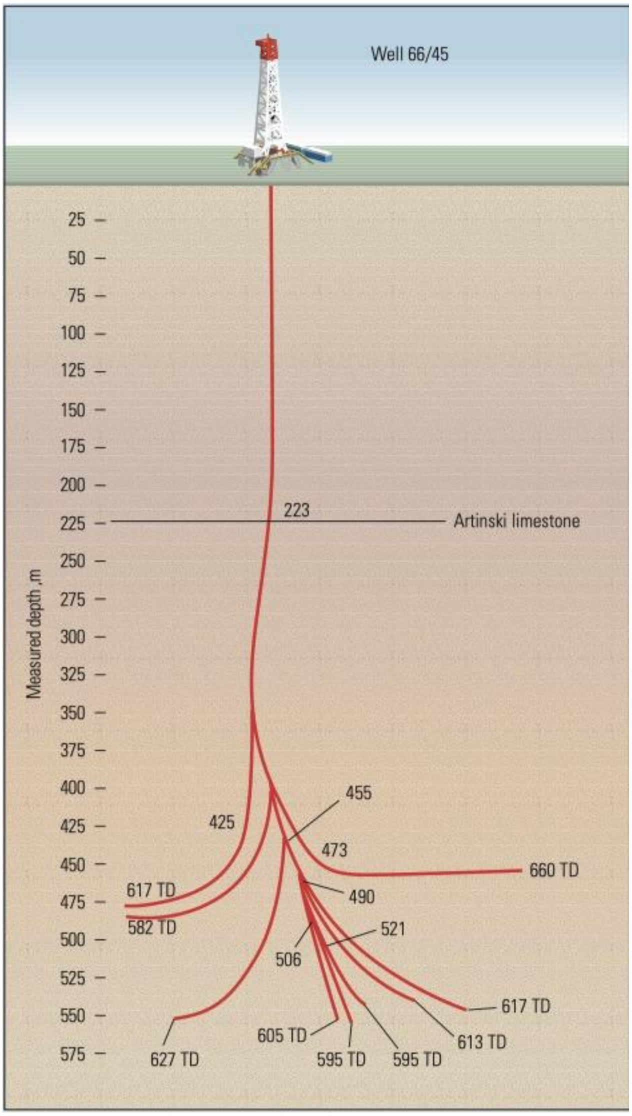

Figure 6: Multilateral well №66/45 drilled by Grigoryan in 1953 (Bosworth 2016).

Most of the multilateral wells drilled since 1953 belong to the level of complexity 1 and 2 according to TAML classification. Drilling of wells of these levels of complexity has become very common. Until 1997, there was confusion about multilateral drilling technology. No universal established terms were describing the technology. There was a lack of a classification of different types of multilateral wells by complexity, risks, types of wellbores joint. Eventually, in 1997, a forum called "Technology Advance - Multi-Laterals (TAML)" was convened at the initiative of Eric Diggins of Shell company (Neftegaz.ru 2013). The forum aimed to unify approaches to further development of multi-bore well drilling technology. At this forum, experts from the world 's leading oil companies shared their experience in using the technology and came to a unified classification of multilateral wells by complexity and functionality.

3.2 Technical advancement of multilateral wells (TAML)

Following the development and publication of The TAML Classification System within the Joint Industry Project (JIP) in 1997, in November 2002 in Calgary, TAML members met and clearly defined the goals of the organization, which was transformed into a non-commercial one based on membership, as well as the possibility of joining new participants. The classification had been changed according to the latest developments in this technology. In English-language publications, the term of Multi-Lateral Technology is widely used, which extends to the entire set of applied technologies for drilling different types of multi-bore wells. In Russian, different terms are used in publications to describe different types of wells and sidetracked wellbores. The wells with laterals (or branches) within one reservoir called multi-branched wells, and the wells drilled from the main borehole at different levels called multilateral.

Today, according to the accepted Technology Advancement of Multi-Laterals (TAML) classification, there are six levels of multilateral wells based on the junction completion and level of hydraulic integrity at the junction. The complexity of multilateral construction increases following the rising level number.

The first level of complexity, TAML 1, is characterized by drilling the main well and the side wellbores without any casing string. In this case, the properties of the rocks have great importance and influence in the success of the operation because the rock strength of the junction, along with the isolation of the formations, depends on them. At the second level of complexity, TAML 2, the main bore is being cased and cemented, while the side wellbores are either being equipped with a liner or left with an open bottom-hole. The third level of complexity, TAML 3, is characterized by a cased and cemented main well, the lateral wellbores are being cased, but not cemented. In the fourth level of complexity, TAML 4, both wellbores are cased and cemented at the junction.

The junction of the main and side wellbores is the most important element of multilateral well construction. At the fifth level of complexity TAML 5, the main and side wellbores are similarly cased and cemented, the pressure integrity is provided by the installation of the packer. The TAML level 5 assumes isolation of a junction, either in a cemented or non-cemented borehole. The last and most complex advancement technology of multilateral wells is TAML 6, which is distinguished by the presence of bottom-hole branching on the main wellbore, and the settled equipment makes it possible to produce separate flows from each well with an isolated junction in each well. Construction of wellbores in multilateral well shown in Figure 7.

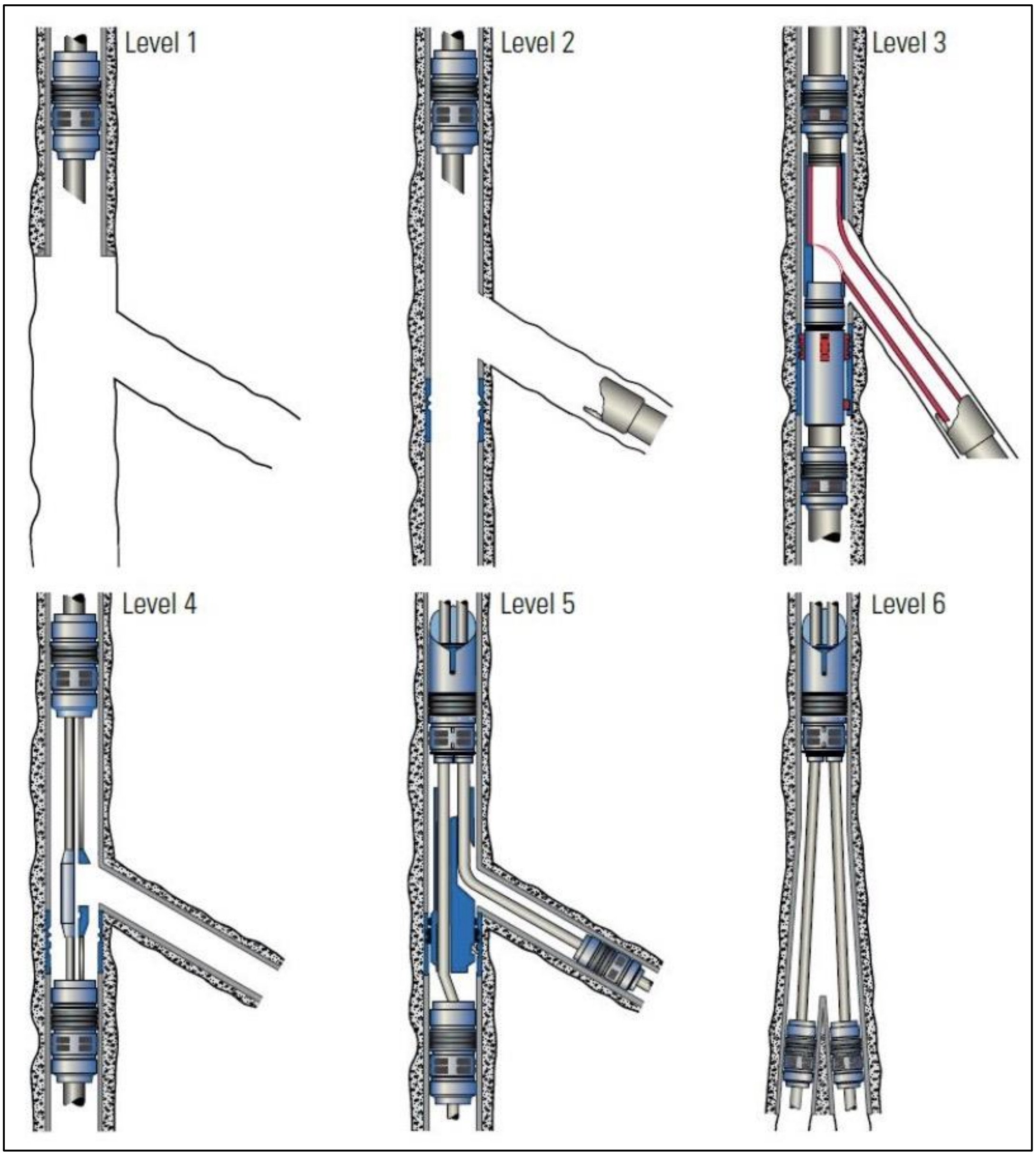

Figure 7: Classification of Multilateral wells by TAML level (Rick von Flatern 2016).

3.3 Complexity level selection (TAML)

Achimov deposits are a complex object of development due to the presence of zones with abnormally high pressure as well as a gas interlayer located above the oil formation. Therefore, it is necessary to accurately analyze the different completion levels of multilateral wells' and select the most optimal one, which will reduce all risks to a minimum. To determine the complexity level of completion and construction of a multilateral well, the advantages and disadvantages of the three levels of complexity (TAML) presented below in Table 10 were analyzed.

Table 10: Advantages and disadvantages of different TAML levels for application at Achimov formations

TAML	Advantages	Disadvantages
Construction of the well according to the 4th level of TAML complexity	• Convenience for workover operations • Both wells are cased and cemented. • Possibility for combining MSHF technologies;	• Risks when removing the diverter tool • Cement doesn't provide sufficient integrity from gas
Construction of the well according to the 5th level of TAML complexity	• Convenience for workover operations • Pressure integrity achieved by packer and completion string	• Risks when removing the diverter tool • Technologically more complex than TAML 4; • Large wellbores required (244.5 mm and more) • Not possible to lower stinger for MSHF

According to the well logging operations on the offset well, gas interlayers have been revealed at the depth interval from 3550 to 3600 m (Figure 8) which possibly can create well integrity problems at the lower TAML levels, where the well construction of lateral doesn't provide sealing at all, and on 4th TAML level where sealing provided by the cementation can cause integrity problems with gas leakage during the well life. The technological problem of TAML 5 is that it is not possible to lower the stinger to conduct fracturing operations because the inner diameter of TAML 5 is narrow.

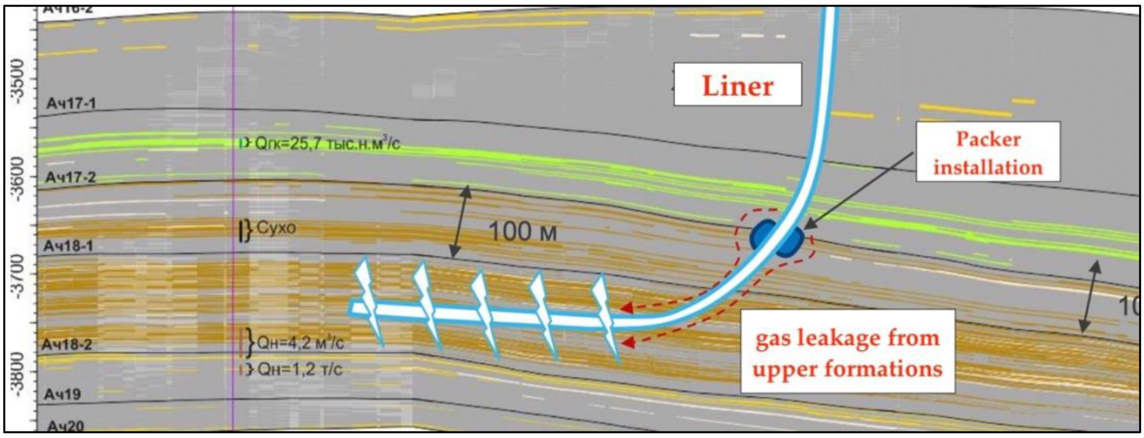

Figure 8: Gas saturated interlayers (green), Achimov's oil formation (brown)

Because of the aforementioned problem, it is recommended to consider the design of convertible TAML 4 level, conduct the hydraulic fracturing in both wellbores, and then reconstruct it to TAML 5 if any well integrity issue is raised.

3.4 Drilling cluster of Yamburg field

The first drilling experience of Gazpromneft in Achimov formations of the YOGC field took place back in 2014, but the project did not reach the production phase due to the complex geology of Achimov formation and abnormal pressures, the company decided to continues the study of Achimov formation and develop appropriate technology besides the field development plan. According to research and studies, in 2019, the company decided to drill two horizontal experimental wells (H-1 and H-2) with five casing strings design, which became an optimal solution for further well construction of the project due to lower cost. Satisfactory results of two drilled wells led to the large-scale field development of Achimov sediments, the company has prepared a development plan and designed a drilling cluster consisting of 13 horizontal wells with a multi-stage hydraulic fracturing stimulation method to maximize production rates, which is the optimal option for increasing oil recovery in the low-permeable formations such in Achimov's. Coordinates of the well cluster with 9 meters safety distance between wells (Table 11), in 3D, and plan views are shown on Figures 9 and 10, where T2 are the entry coordinates to the reservoir, and T3 ends of horizontal sections presented in Table 12. As seen in the figures, the drilling cluster has a symmetrical shape for the greatest coverage of oil-bearing zones of Achimov formations.

Table 11: Well cluster coordinates

Cluster name	Easting, m	Northing, m
1_14	551500	7529800

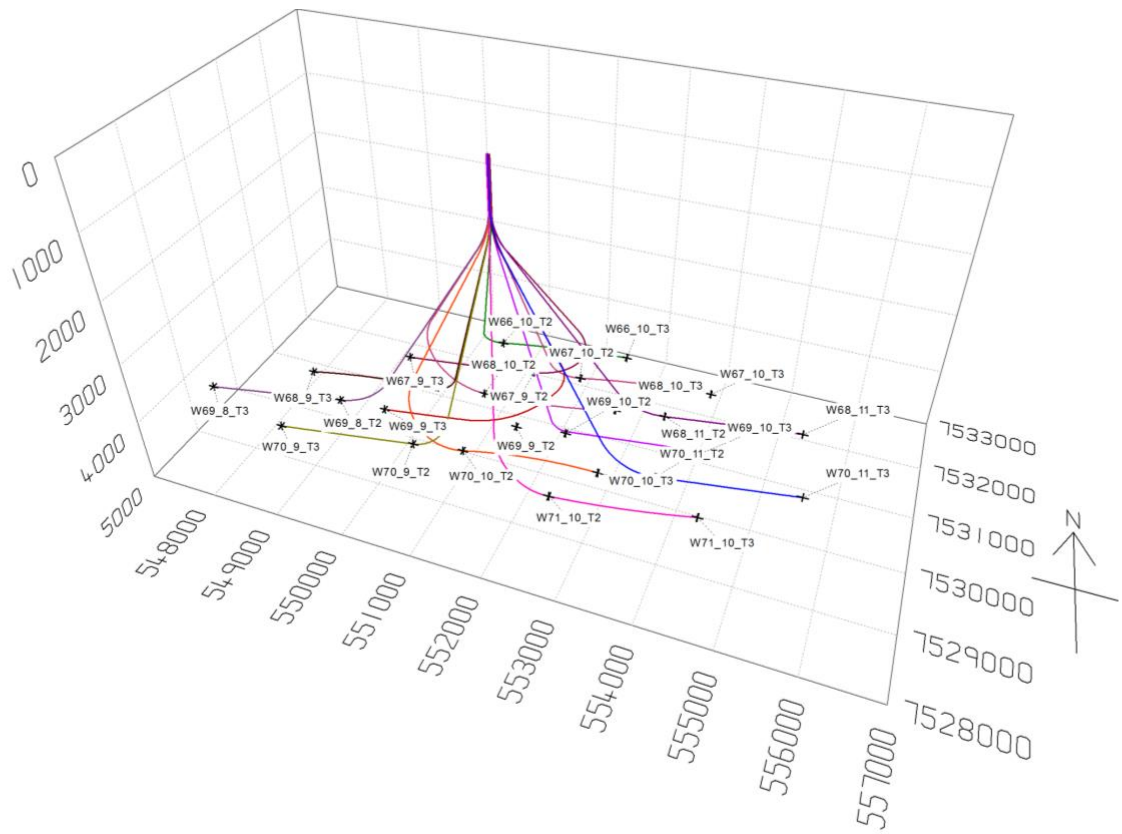

Figure 9: 3D view of the well cluster in the YOGC field.

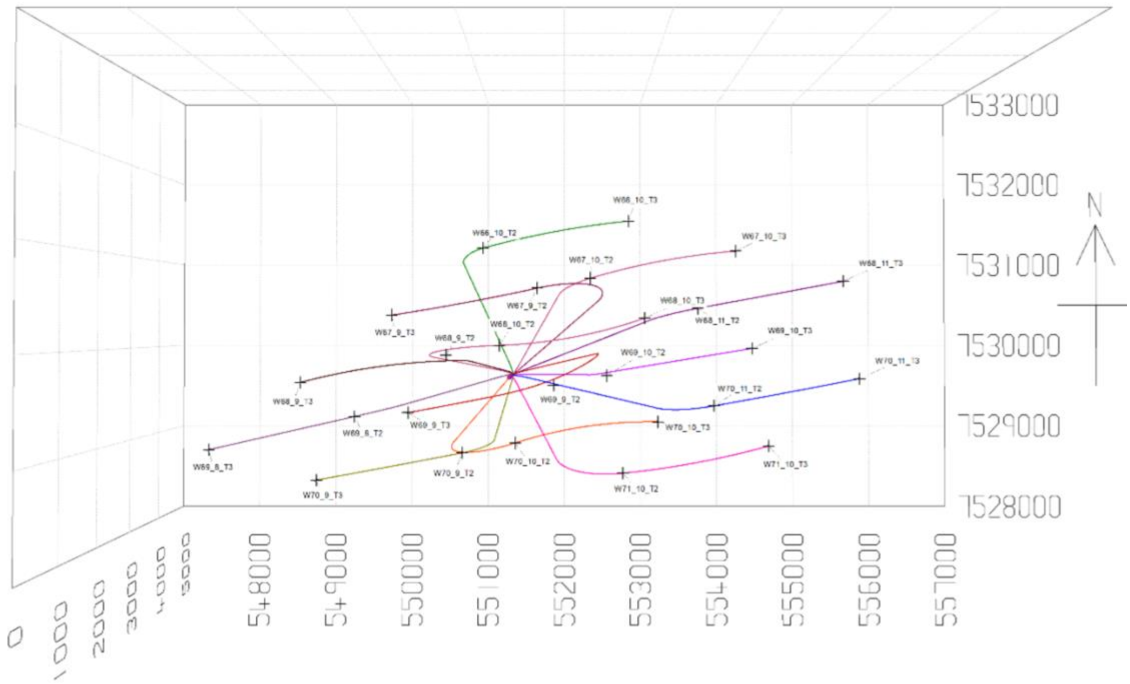

Figure 10: 2D view of the well cluster in Achimov formation

Table 12: Coordinates of wells in the cluster.

Well name	Reservoir entry and endpoints	Easting, m	Northing, m	Depth, m
w66_10	T2	551009	7531141	3800
	T3	552782	7531453	3800
w68_9	T2	550559	7529904	3800
	T3	548787	7529591	3800
w68_10	T2	551207	7530018	3800
	T3	552980	7530331	3800
w68_11	T2	553628	7530445	3800
	T3	555401	7530758	3800
w70_9	T2	550757	7528781	3800
	T3	548985	7528469	3800
w70_10	T2	551405	7528896	3800
	T3	553178	7529208	3800
w70_11	T2	553826	7529322	3800
	T3	555598	7529635	3800
w67_9	T2	551671	7530679	3800
	T3	549898	7530366	3800

Well name	Reservoir entry and endpoints	Easting, m	Northing, m	Depth, m
w69_8	T2	549448	7529129	3800
	T3	547675	7528817	3800
w69_9	T2	551869	7529556	3800
	T3	550096	7529243	3800
w69_10	T2	552517	7529670	3800
	T3	554289	7529983	3800
w71_10	T2	552714	7528548	3800
	T3	554487	7528860	3800
w67_10	T2	554091.22	7531105.54	3800
	T3	552318.56	7530792.98	3800

3.5 The trajectory of designed multilateral well - ML-1

After analysis of well cluster, geology review the following Gazprom requirements have been considered:

- to reduce well interference, the distance between reservoir entry points was established as 600 m;
- the parallel arrangement of horizontal sections at the same depth was arranged.

The aforementioned requirements were taken into account to design the trajectory of multilateral well ML-1. After the drilling analysis and optimal trajectory determination, the project wells W68_11 and 70_11 were considered as the best candidates for multilateral well Figure 11.

After defining best well candidates with reservoir entry points fulfilling obligations of Gazprom Neft STC, the trajectory of Multilateral well (ML-1) was designed. 3D profile of the well ML-1 with two laterals and its plan view is presented in Figures 12 and 13.

Multilateral well construction

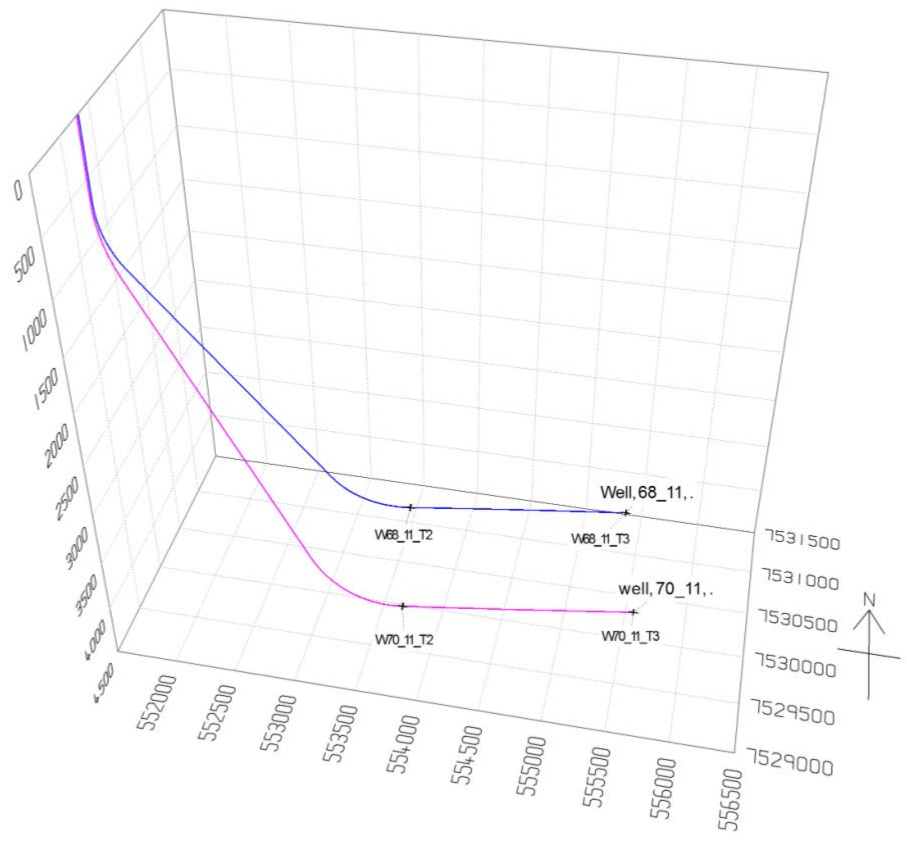

Figure 11: 3D profile of candidate wells for ML-1.

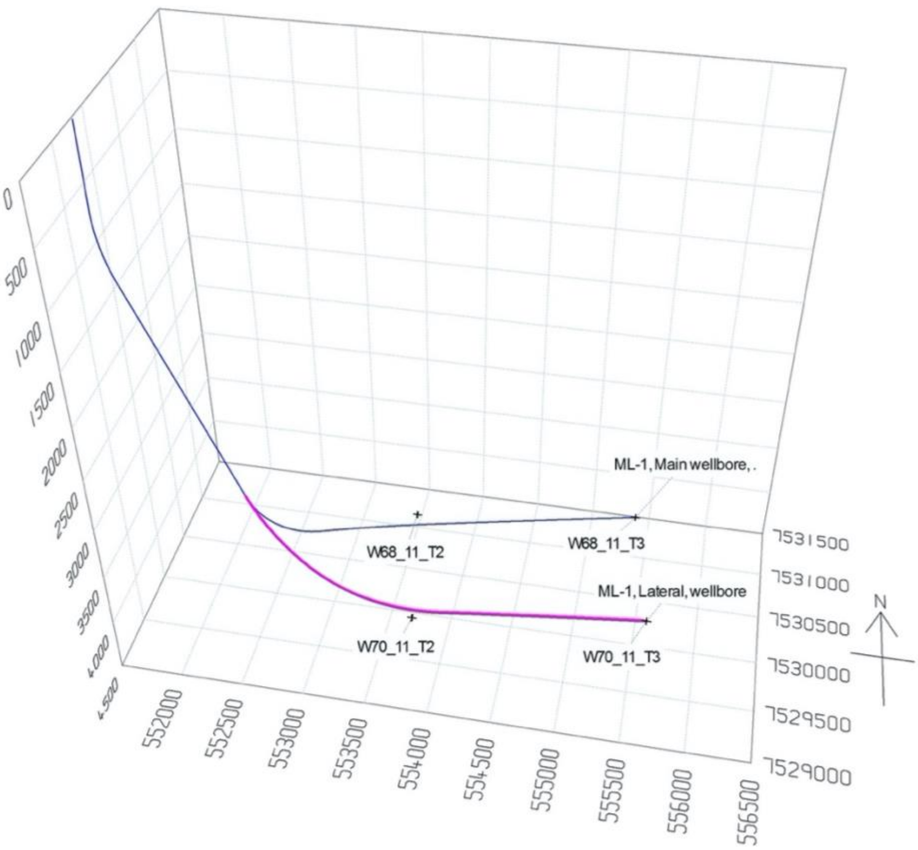

Figure 12: 3D profile of Multilateral well ML-1.

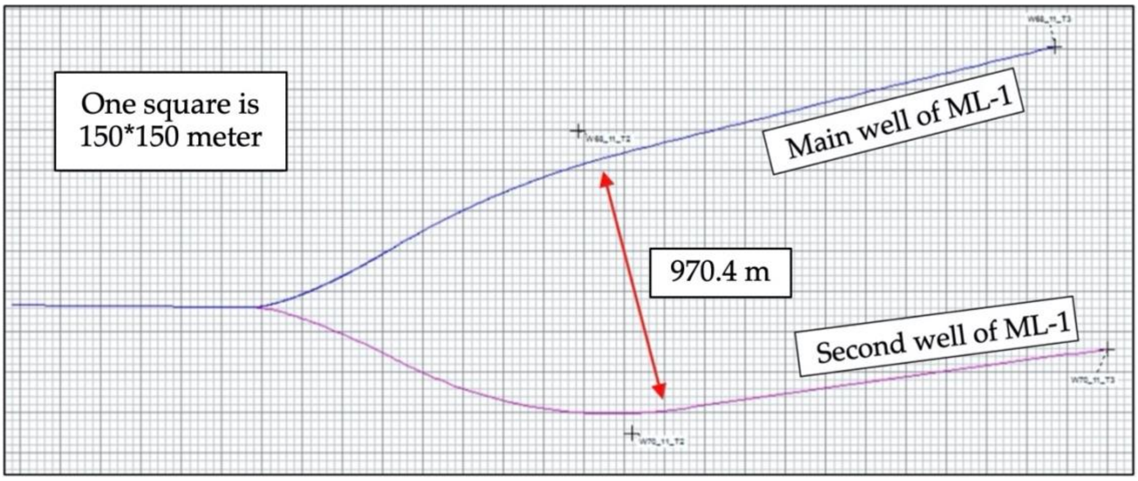

Figure 13: Plan view of the well ML-1 with the distance between T2 points.

3.6 Well profile and casing design of ML-1

The well profile selection is carried out taking into account the requirements for drilling cluster wells, the strength characteristics of the formations, methods, and technical tools used during well's operation. In this master thesis Multilateral well with 2 parallel horizontal wellbores is designed based on previous drilling experience of first experimental wells with J type profile in the abnormally high-pressure condition of Achimov formation. Well profile sections presented in Table 13:

Table 13: the profile of the well ML-1 in sections.

№	Section name	TVD (m)	Md (m)
Main wellbore			
1	Vertical section	0 - 700	0 - 700
2	Build-up section	700 – 1300	700 – 1300
3	Tangent section	1300 – 3124.7	1315 – 3380.1
4	2nd build-up section	3124.7 - 3800	3380.1 - 5100.2
5	Horizontal section	3800 - 3803	5100.2 - 6759.72
Lateral wellbore			
3.1	2nd wellbore milling/kick of point	3214 - 3600	3380 -5278.1
3.2	2nd wellbore's Horizontal section	3800 - 3803	5278.1 – 6870.6

This type of well profile is the most acceptable and allows to reduce the length of the wellbore, reduce friction forces of the drilling string due to elimination of strong deflections of the wellbore path, reduce the loads on the drilling rig during tripping operation and casing running, provide trouble-free stable running of the well equipment (logging tools, pump, etc.). In the construction of each particular well, the length of the vertical section is selected depending on the displacement of the well bottom from the vertical, and the safety condition of the well colliding in the cluster. The safety distance between wells in the cluster of the Yamburg field is 9 m. In Figure 14 well profile presented in vertical and plan views.

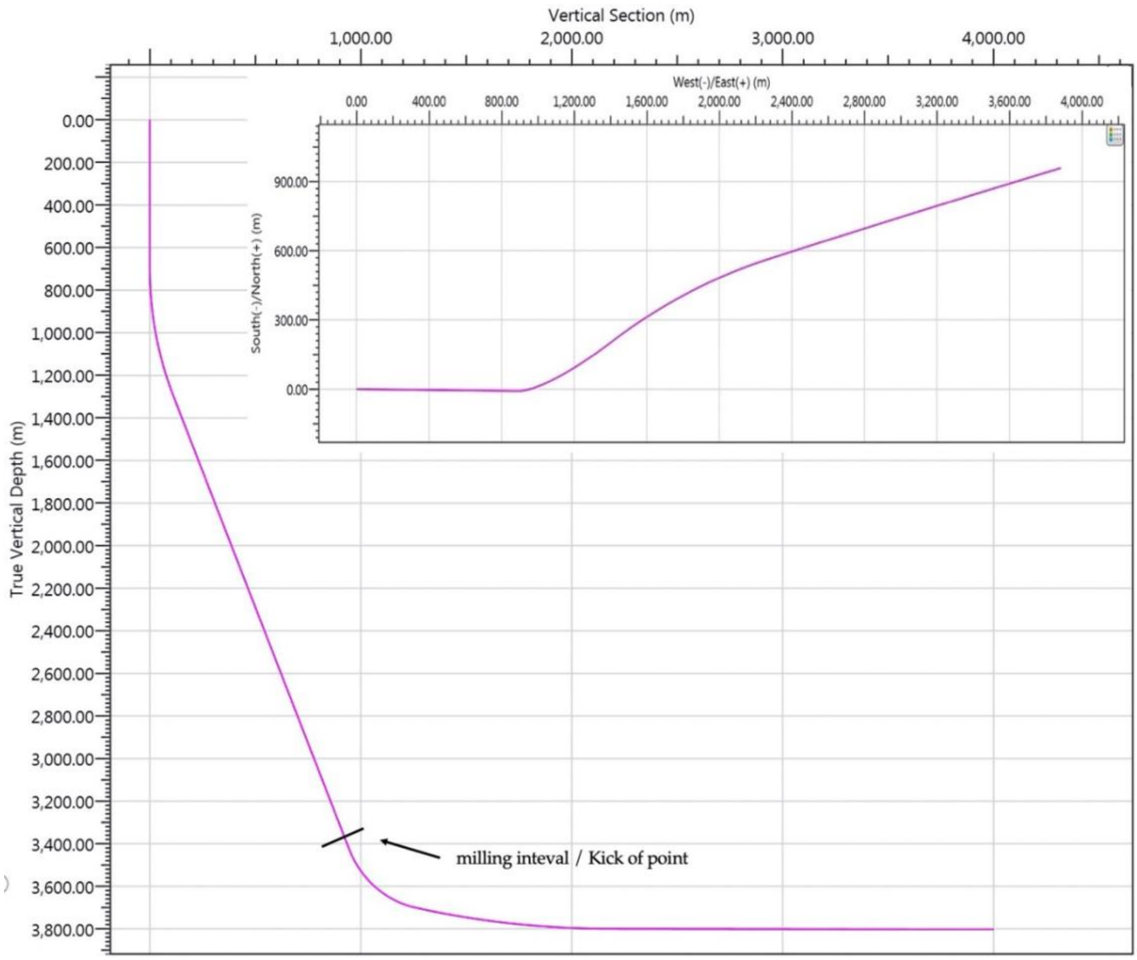

Figure 14: Vertical and plan views of the main wellbore.

According to the international experience of multilateral wells drilling, it is recommended to mill "window" in intervals located below clay rocks and intervals with good quality of cement sheath. Before the whipstock is lowered, the column should be checked with a casing collar locator. The diameter and length of the pattern shall be greater by 3 - 4 mm and 2 - 3 m, than the corresponding sizes of the whipstock. Then, the location of two-three couplings of the casing is determined, between which it is planned to mill/drill the window. The planned measured and true vertical depths for milling the lateral wellbore are 3380 m and 3224 m. Well profile presented in vertical and plan views on Figure 15.

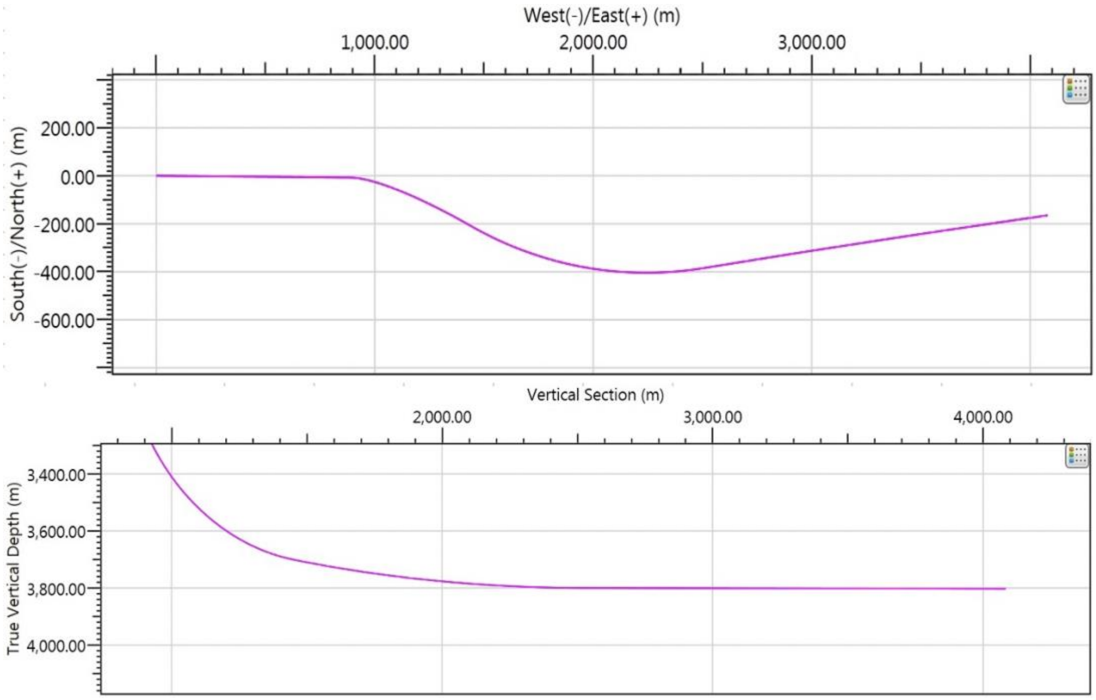

Figure 15: Plan and vertical views of 2nd wellbore.

The casing scheme of the multilateral well ML-1 is presented in Figures 16 and 17, casings setting depths, and grades are shown in Table 14. The CasingSeat and StressCheck software's have been used for analysis.

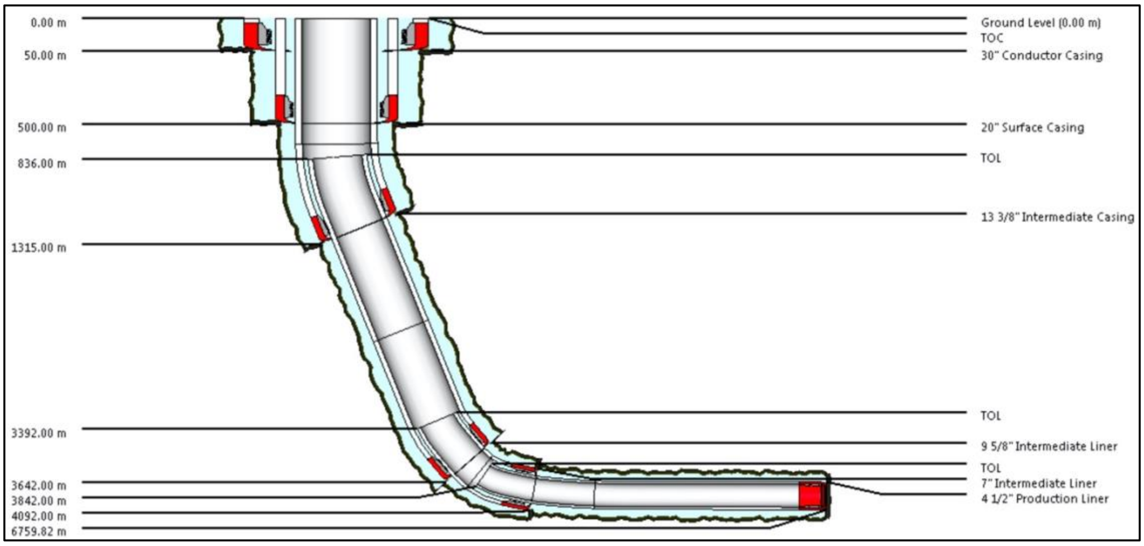

Figure 16: Main wellbore casing scheme of ML-1

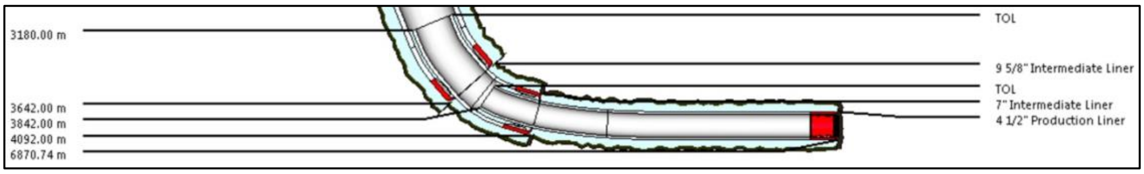

Figure 17: Casing scheme of the lateral wellbore.

Table 14: Casing scheme details

Casing name	Casing setting depth interval (m)	OD, (in.)	Casing grades	Weight (tons)
Main wellbore				
Conductor	0 – 50	30	X–46	24,003
Surface	50 – 500	20	J–55	17,831
Intermediate	500 – 705.4	13 3/8	P–110	10,363
	705.4 – 1315		N–80	10,973
1st intermediate Liner	836 – 2422.8	9 5/8	N–80	7,163
	2422.8 – 3642		T–95	8,153
2nd Intermediate Liner	3392 – 3787.2	7	T–95	4,877
	3787.2 – 4092		P–110	4,877
Production Liner	3842 – 6759.8	4 1/2	P–110	1,676
Lateral wellbore				
1st Intermediate Liner	3392 – 3787.2	7	T–95	4,877
	3787.2 – 4092		P–110	4,877
Production Liner	3842 - 6870.7	4 1/2	P–110	1,674

3.7 Anti-collision analysis.

Cluster drilling refers to a method of drilling wells in which wellheads are located on a common site, and bottoms according to the geological grid of the field development. Cluster drilling has several significant advantages.

First of all, it is economically profitable, as at the same time the costs and time for the development of well sites are significantly reduced. Besides, cluster drilling is also beneficial from the environmental point of view, as it allows to significantly reduce the area of land occupied under drilling, as well as to reduces the costs of environmental protection measures.

When drilling wells from cluster sites since wellheads are located close to each other, severe accidents related to wellbores colliding are possible. The anti-collision analysis is used to prevent this phenomenon.

After the selection of candidates for multilateral well and well trajectory planning has been made, the anti-collision analysis was performed to prevent wellbores from colliding. The anti-collision analysis made in this master's thesis includes the Separation Factor (SF) and Ladder plots.

The separation factor - SF defines a ratio between the wells' centers distance and the sum of the ellipsoids of uncertainty along with the measured depth (equation 2).

$$SF = \frac{\text{C2C distance}}{\text{EOU(subject well)+EOU(offset well)}} \quad (2)$$

Figure 18 shows an example of the SF calculation at a certain depth of the subject well.

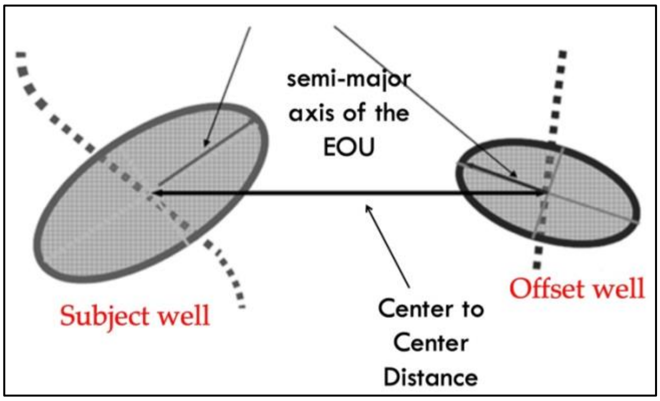

Figure 18: An example of the SF calculation at a certain depth (Elmgerbi 2018).

The ellipses on uncertainty define the well survey error at certain depths. Errors could occur, due to different sources: measured depth, azimuth, inclination, etc. The Compass module of Landmark software has a built-in International error propagation model - "ISCWSA" (Industry Steering Committee for Wellbore Survey Accuracy Error Model), which considers uncertainties during the well trajectory planning. The software has three alarm levels for defining wells collision risk. Table 15 shows the alarm levels of Compass software. It can be seen that the higher level, the higher the risk of wells colliding.

Table 15: The Alarm levels of the Compass software according to the ISCWA error propagation model.

Alarm level	Separation Factor
Level 1	≤1.5
Level 2	≤1.2
Level 3	≤1

Figure 19: Present separation factor plot of the main wellbore of ML-1 versus to all wells in the cluster. As can be seen from the figure, at the wells KOPs that SF between main well and some of the other wells in the cluster is increasing. It is explained that the wells' build-up sections are in the same azimuth directions. The figure also shows, that at the depth 3380 the lateral wellbore of ML-1 (light green), moves up from the point when SF is 0, which means that the trajectory of wellbore started from the main well. It is also seen that none of the wells in the cluster is close to the warning alarm level, and so there is no risk for wells colliding.

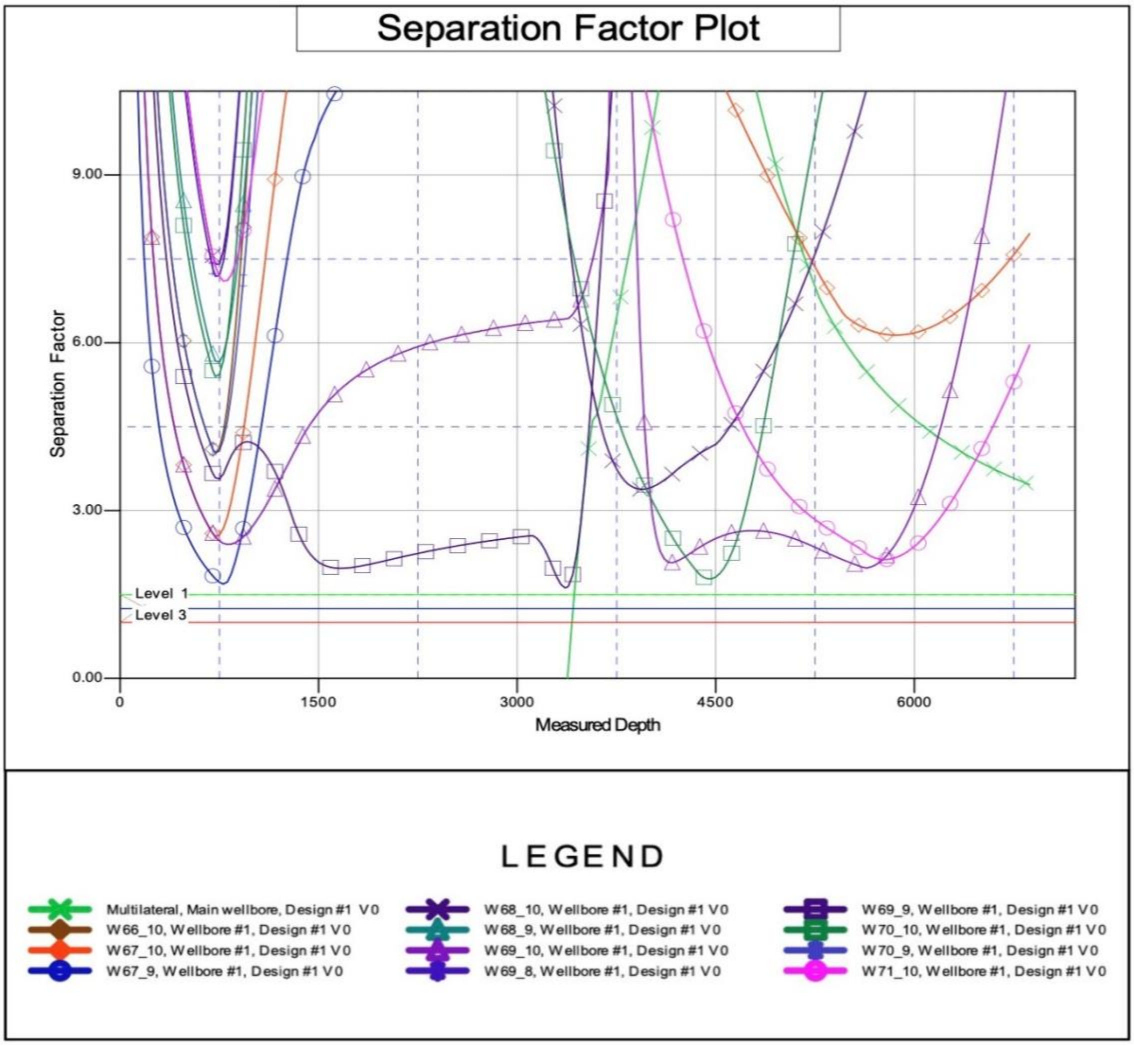

Figure 19: Separation factor plot of ML-1.

The ladder plot is a simple graph of the offset wells' separation concerning subject well along with the measured depth. These graphs are extremely useful for determining which well in the cluster to watch at a certain depth during the real-time monitoring of the drilling process. Figure 20 shows the ladder plot for all wells in the cluster concerning the main wellbore of ML-1. The distance from the Main well of ML-1 and other wells is increasing with measure depth and there is no risk for wells colliding.

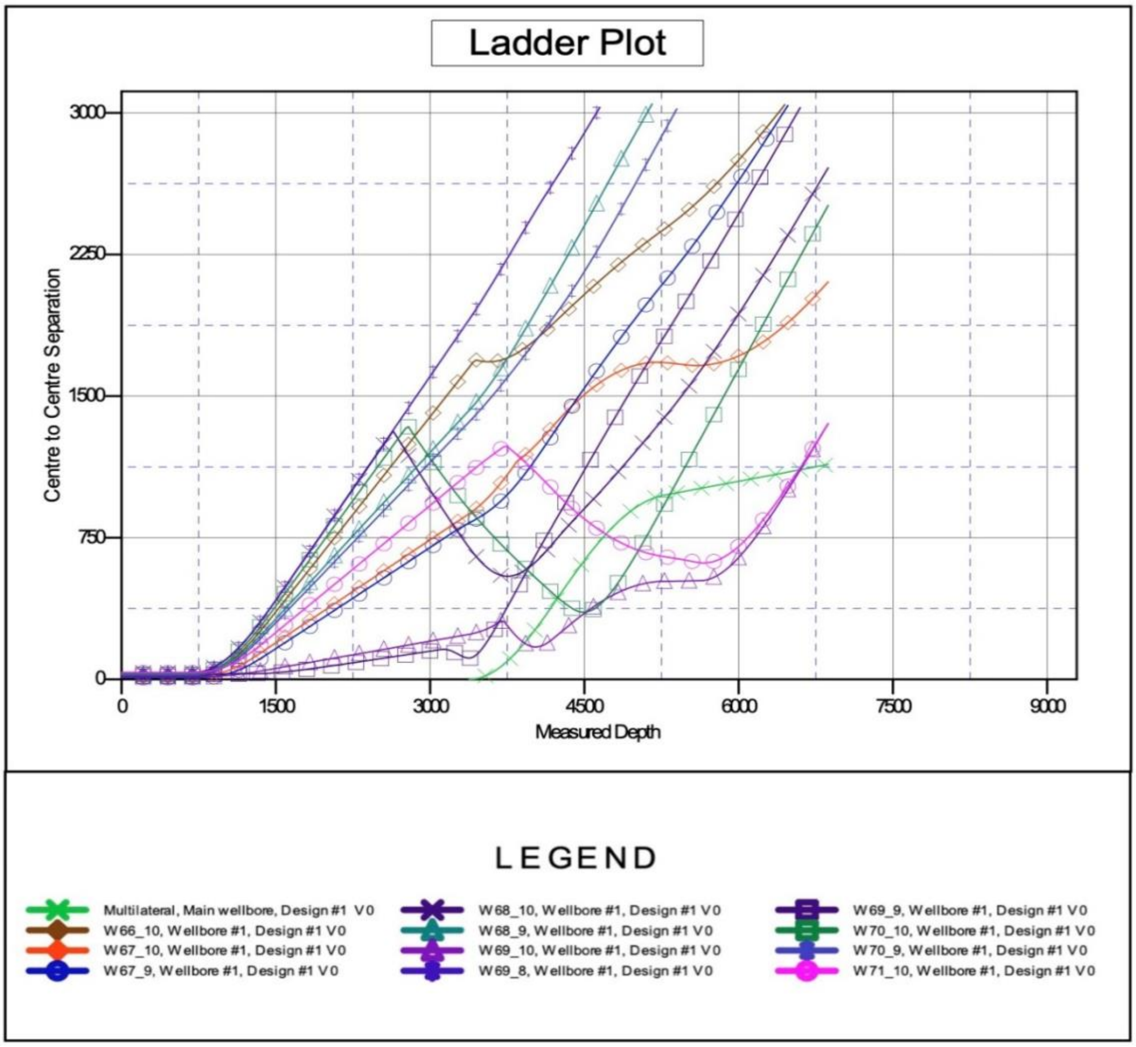

Figure 20: Ladder plot of ML-1.

3.8 Drilling plan for ML-1

Designed drilling modes and drill string components of well ML-1 presented below in Tables 16 and 17.

Table 16: Drilling modes and parameters.

Intervals MD, m		Drilling method	Axial loads kN	Torque, N·m	Rotating speed RPM	Flow rate, L/m	Rate of penetration m/h
from	to						
Main wellbore							
0	50	rotary	10 - 30	1000	60 - 120	3331	15 - 20
50	500	rotary / PDM	20 - 100	2840	up to 40	3331	10 - 15
500	700	rotary / PDM	20 - 100	3330	up to 40	2972	15 - 20

Intervals MD, m		Drilling method	Axial loads kN	Torque, N·m	Rotating speed RPM	Flow rate, L/m	Rate of penetration m/h
from	to						
700	1315	rotary / PDM	20 - 100	6140	up to 40	2972	15 - 20
1315	3642	rotary / PDM	20 - 100	19710	up to 40	2536	15 – 25
3645	4092	rotary + RSS	20 - 100	21828	100 - 130	1401	30 - 45
4092	6759.2	rotary + RSS	20 - 100	24403	100 - 150	850	30 – 45
Lateral wellbore							
3392	3842	rotary + RSS	20 - 100	22715	100 - 150	1340	30 - 45
3842	6810.6	rotary + RSS	20 - 100	24392	100 - 150	820	30 – 45

Table 17: BHA and drilling string components.

Casings	№	Drill string components	Length, (m)	Distance from the surface, (m)
Main wellbore				
Conductor 0 – 50	1	7′′ DC, 31.9 ppf	18.12	18.22
	2	8′′ DC, 49.7 ppf	30	48.12
	3	32 1/4′′ reamer	0,69	48.81
	4	8′′ sub	0,5	49.31
	5	26′′ bit	0,69	50
Surface 50 - 500	1	4′′ 1st class DP, 11.85 ppf, E	438.528	443.64
	2	7′′ DC, 31.9 ppf	18	461.64
	3	8′′ DC, 49.7 ppf	25	486.64
	4	8 1/2′′ stabilizer	1.524	488.164
	5	9 5/8′′ PDM	10.296	498.46
	6	7 7/8′′ sub	0.914	499.374
	7	26′′ bit	0.63	500
Intermediate casing 500 - 1315	1	4′′ 1st class DP, 11.85 ppf, E	1,196.76	1,196.76
	2	5′′ DC, 49.7 ppf	100	1,296.76
	3	9 1/2′′ MWD	5.2	1,301.96
	4	8 1/2′′ stabilizer	1.524	1,303.48
	5	9 5/8′′ PDM	10.296	1,313.78
	6	6′′ sub	0.914	1314.7
	7	17 1/2′′ bit	0.305	1,315.0

Casings	№	Drill string components	Length, (m)	Distance from the surface, (m)
1st Intermediate liner 1315 - 3642	1	5 1/2'' 1st class DP, 24.7 ppf, S	3,055.71	3,055.71
	2	8'' Hyd. Jar	10.241	3,065.95
	3	6 5/8'' DC, 70.50 ppf	550	3,615.95
	4	9 1/2'' LWD	8.5	3,624.45
	5	9 1/2'' MWD	5.2	3,629.65
	6	9'' stabilizer	1.524	3,631.17
	7	8'' PDM	9.610	3,640.78
	8	6'' sub	0.914	3,641.70
	9	12 1/4'' bit	0.305	3,642.0.
2nd intermediate liner 3642 - 4092	1	5'' DP	3,751.8	3,751.81
	2	6 1/2'' DC 69.15 ppf	300	4,051.81
	3	7 3/4'' Hyd. Jar	11.460	4,063.27
	4	6 3/4 ''LWD	8.5	4,071.77
	5	6 3/4'' MWD	9.144	4,080.91
	6	6 1/4'' stabilizer	1.524	4,082.44
	7	7'' PDM	8.345	4,090.78
	8	7 7/8'' sub	0.914	4091.7
	9	8 1/2'' bit	0.305	4092.0
Production liner 4092 - 6759.8	1	4'' Premium class DP, 15.70 ppf, S	3,526.39	3,526.39
	2	4'' DC, 31.9 ppf	500	4,026.39
	3	4'' Premium class DP, 15.70 ppf, S	600	4,626.39
	4	3 1/2'' 1st class DP, 15.50 ppf, S	900	5,526.39
	5	3 1/2'' 1st class DP, 13.30 ppf, S	1200	6,726.39
	6	4 3/4'' Hyd. Jar	9.754	6,736.15
	7	4 3/4'' LWD	6.858	6,743.01
	8	3 3/4'' stabilizer	1.524	6,744.53
	9	4 3/4'' RSS	14.98	6,759.51
	10	6'' bit	0.305	6,759.82

Multilateral well construction

Casings	№	Drill string components	Length, (m)	Distance from the surface, (m)
Lateral wellbore				
Intermediate liner 3392 - 4092	1	4 1/2′′ 1st class DP, 16.6 ppf, S	3,565.30	3,565.30
	2	6 1/2′′ DC, 88.86 ppf	300	3,865.30
	3	7 3/4′′ Hyd. Jar	11.460	3,876.76
	4	6 5/8′′ DC 67.93 ppf	200	4,076.76
	5	8′′ LWD	5.2	4,081.96
	6	6 1/4′′ stabilizer	1.524	4,083.48
	7	8′′ PDM	7.3	4,090.78
	8	7 7/8′′ sub	0.914	4,091.70
	9	8 1/2′′ bit	0.305	4,092.00
Production liner 4092 - 6870.7	1	4′′ Premium class DP, 15.70 ppf, S	3,237.32	3,237.32
	2	4′′ DC, 31.9 ppf	600	3,837.32
	3	4′′ 1st class DP, 14.00 ppf, S	600	4,437.32
	4	4′′ Premium class DP, 14.00 ppf, S	1400	5,837.32
	5	3 1/2′′ 1st class DP, 13.30 ppf, S	1000	6,837.32
	6	4 3/4′′ Hyd. Jar	9.754	6,847.07
	7	4 3/4′′ LWD	6.858	6,853.93
	8	3 3/4′′ stabilizer	1.524	6,855.46
	9	4 3/4′′ RSS	14.98	6,870.44
	10	6′′ bit	0.305	6,870.74

4. Intelligent completion solutions

The petroleum industry was largely formed by the production, exploration, refinement, and consumption of natural hydrocarbons. Several tasks of expanding reserves volume, improving technology, increasing production degree and transportation, become the priority for sustaining the increase rate of the modern world industry. The consumption of petroleum products has led to an increase in its demand, which, together with the limb of the world's reserves, has reached to the current oil rates. The need and value of raw materials have made possible the quick development of drilling, completion and production technologies, and the industry itself. The improvement of technologies made it possible to produce fields with low filtration and collector properties like in Achimov formations of the YOGC field, which in previous years was impossible to find an approach that provided positive profitability. At the same time, there have been and continues to be a gradual depletion of explored deposits with high collector and filtration properties. Actual objects of development have different complicating factors, such as high depth of occurrence, poor permeability, mobile gas cap, non-uniform fractures, low formation or abnormal pressures, etc. Currently, in Western Siberia at almost all Russian companies, the largest part of assets are low permeable collectors. (D. V. Kozlov 2018)

Current characteristic features for developing collectors with low-filtration properties are the increase of wells' density grid, fluid stimulation using different hydraulic fracturing (HF) methods or acidizing drilling wells with the large horizontal sections, and an extensive system of formation pressure. It would seem that low permeability should cause very slow hydrodynamic movements in the formation. Still, geologically natural inhomogeneities and artificially made fractures, as well as large contrasts of bottomhole and formation pressures, cause active interference of wells. This interference can also be positive when it comes to uniform formation production and maintenance of formation pressure. However, more often, active interfacing carries difficulties and hazards, such as premature flooding from the injection well or reduction of formation pressure with the fluid degassing that prevents oil filtration in the formation. Even in the absence of underlying waters and high initial water saturation, there is a regular decrease in effective permeability with the water content increase in the fluid. The multiple problems caused by wells interaction and change of formation parameters makes control and monitoring of well the key to efficient petroleum exploitation. Therefore, the tasks of building a high-quality and economically justified monitoring system with including methodological implementation, are becoming increasingly important every day.

4.1 Concept of intelligent well

One of the most promising among the innovative technologies that can ensure the increase of reserves may be the idea of intelligent wells, which allows monitor, control, and manage productive zones without in-well operations. With real-time monitoring and production control of the productive formations from the surface, the technologies of intelligent wells may ensure maximum drainage area of the formation and accurate well targeting using the latest innovations in the field of drilling and completion, which heads to the notable increase of oil recovery and acceleration of production. One of the central obstacles for the development of low permeable multi-compartmentalized reservoirs with horizontal wells is irregular fluid inflow into the wellbore due to the creation of water coning and gas cusping.

To balance the inflow and prevent the early formation of cone water or gas, the well may be equipped with sectional intelligent control elements. This idea creates the conception of intelligent or "smart" well. The completion of the intelligent well divided into several intervals isolated from each other by packers. This makes it possible to control the inflow or injection into each of the intervals separately. Control may be carried out as by passive devices limiting the inflow from different low permeable interlayers, thereby balancing the distribution of the fluid flow along the wellbore, and using active inflow control valves (ICV). Which directly controlled by engineers and giving the most flexible control of fluid flow. In 2016, around 2200 wells were equipped with inflow control valves for optimizing well operations (Carvajal 2018).

The conducted research from the fields around the world shows that the total oil recovery can be increased by 9% by the installation of one single well at each field. The research also reveals that the oil recovery factor can be increased by around 25% with the full implementation of smart wells into the field. The described economic assessment was formed by the industrial implementation of smart wells, which include the following examples.

Kuwait Oil Company (KOC): At the Minagish field in the water-flooded reservoir, the water cut was decreased from 75% to 25%. At onshore stacked multilateral wells with 20 internal control devices (ICD) and an ICV per branch. The well had a 1524m lateral section for each branch using an ICV port per lateral.

Statoil: At the Snorre B field, in subsea water alternating gas (WAG) project. The water and gas breakthrough, on average, per producer well, was delayed by six months, keeping production period for a longer time than expected without smart wells. The ICVs were installed on 10 wells to control water injection, whereas gas injection was controlled by time.

Saudi Aramco: At South Shaybah Field, by application of intelligent solutions in multilateral well in "maximum reservoir contact" project.

The project highlights a multibranch well with a total of 12.000m of drilled holes using five sections controlled with ICVs. The well-produced 12,000 barrels per day, when compared to the traditional horizontal well with 1000m horizontal section producing 3000 barrels per day (Konopczynski 2008).

Case studies from fields in the KOW, Statoil, and Saudi Aramco have demonstrated how the technology of intelligent wells can help increase production at a lower cost, identify the potential of either new or old fields and significantly reduce water inflows. The basis of the modern intelligent solutions did not change much, and it uses the same downhole valves and sensors controlled from the surface, valves used to control inflow from individual zones or lateral wellbores, and permanent sensors for measuring downhole pressure, temperature, and fluid flow. According to the chronology of technology evolution, these solutions are successors of conventional inflow control valves lowered and controlled by cable. In addition to the pressure and temperature measuring sensors, the smart well may also have flow meters in each zone and fiber-optic temperature sensors distributed over the wellbore length. Equipment for well monitoring has the function of transmitting information to the surface in real-time without the need to carry out downhole operations.

The completion system of modern intelligent wells consists of four main components:

- The feed-through packer – the separation between two zones. The multi-channelling of packer is needed for hydraulic control lines or electric cables for valves and the monitoring systems;
- The inflow control valves (ICV) – valves with remote control
- Inflow control devices (ICD) – creates an additional pressure drop rate which manages the flow of liquid into the well.
- Control lines - connection with the valve is carried out using hydraulic control lines. Moreover, the electric cables can be used for capturing the real-time recordings from the measurement tools. Hydraulic control lines are the most common technology.
- Monitoring tools, sensors of pressure and temperature, or the fiber-optic system for the distributed measurements
- Data acquisition system – the ground-based system for collecting and processing information and management.

4.2 Communication and power equipment

Common modern completions use multiple control lines, which could be represented by hydraulic, electric, and fibre-optic lines.

4.2.1 Hydraulic lines

The hydraulic lines are used to supply power that is necessary to control different downhole intelligent completion parts. Hydraulic control of ICVs is the preferred control architecture in current intelligent completions. This hydraulic control architecture is generally referred to as a "direct hydraulic" system in the industry. Two hydraulic lines from the surface connect to the open and closed side of a balanced piston of an ICV. Pressure on any one of the two lines will move the piston in the direction of the applied hydraulic force. The hydraulic line system uses the N+1 control lines to control the N number of ICV. Every ICV has its hydraulic line connected to the actuation chamber. The oil and gas industry used a standardized quarter inch outer diameter lines. (Elias Garcia, and Savio Saldanha, Halliburton 2016)

4.2.2 Electric lines

The intelligent completions may be equipped with electric lines. The electrical lines are used either for transmitting the signal from downhole measurement gauges or used in combination with hydraulic lines to control the ICVs. In this case, they are called electrohydraulic lines. This means that the inflow control valves are controlled or adjusted by a mechanical method like a solenoid, threaded drive, or the ball drive method, and by the motor or the hydraulic pump. Electric lines have reliability issues connected with tiny leakage, which can destroy the whole system over time. The most significant drawback of the electrical control line is the presence of a cable in the completion assembly, which creates difficulties during lowering. It also takes more time to lay and protect the cable from mechanical damage, cannot rotate the column, and needs to deliver the downhole module to the landing place. (Elias Garcia, and Savio Saldanha, Halliburton 2016)

4.2.3 Fiber – optics

Fiber optics systems used for monitoring and investigating the wells all around the world. In this technology, the data transmission line and the distributed sensors is an optical fiber, through which light pulses generated by the laser are being transmitted. With the help of special optical devices and mathematical software, reflected signals are being read. Additional equipping of fiber-optic systems with distributed sensors of temperature, flow rate, composition, and pressure may enable the company to use the system for designing intelligent or "smart" wells, for better monitoring during the wells' lifecycle. The modern conception of an intellectual well and field based on the organizational production and field exploitation of multifunctional fiber-optic sensors and devices specified in the implementation of the following two outlines.

The first outline is concentrated in the formation of the intelligent monitoring and field exploration, main technical solutions for the intelligent designs, and cyber management of the process.

The second outline is applied to the formation of a technical and technological complex for monitoring and controlling operations of intelligent formations, wells, and fields. The second outline should involve the construction of well designs equipped with fiber-optic sensors and devices for monitoring well and formation parameters concerning the exploration of two well types.

- Downhole equipment for the existing well stock with fiber-optic sensors lowered to the well bottom on the coil tubing;
- bottom design for newly drilled wells, which enables selectively open and measure the parameters of the formation/stage of HF and control production modes of each.

The operation of sensors located at various depths and measuring various flow parameters can be used on the same fiber core. Optical fiber is used in the manufacturing of the sensors and simultaneously serves as a communication channel, representing a thin thread of glass with a core sealed hermetically with cladding and then a buffer layer. All this is enclosed in an outer jacket of stainless steel. The construction of optic-fiber is shown in Figure 21.

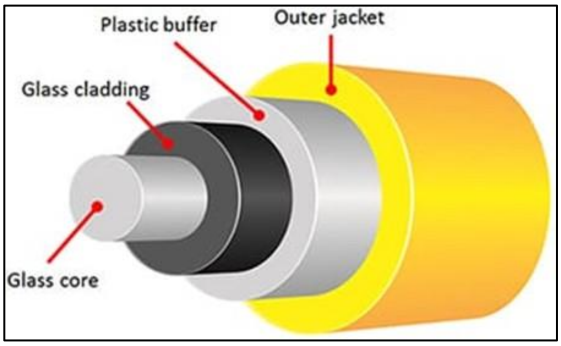

Figure 21: Construction of optic-fiber cable.

The material used to manufacture the sensors is the glass core of an optical fiber, in the body of which, "disturbances" were created by laser using a special technology.

Disturbances cause changes in the parameters of the transmitted or reflected light flux in proportion to changes in the measured medium parameter: temperature, pressure, vibration, etc. Depending on the monitoring tasks, multiple sensors may be placed in the wellbore on a one fiber optic cable, measuring depth-specific parameters of the downhole medium or downhole pumping equipment. As a result of this, the assembly of the measuring elements and the communication channel for each well should be different. The durability of fiber optic cables and sensors surpasses 40 years.

4.3 Control equipment

In recent years companies providing services in the field of services and completion has developed several types of downhole control valves. The Control valves are identified based on their construction and main functions. The primary category includes passive devices, autonomous passive devices, and reactive-actionable control valves, which are described in this subchapter.

4.3.1 Passive devises – Inflow control devices (ICD)

The Passive control devices or "ICD" creates a supplementary pressure drop rate which regulates the flow of liquid into the well. The generation of balanced drop rates across the whole horizontal well helps to bypass early gas and water breakouts. This type of control system is being equipped at the surface with other completion equipment, and can't be adjusted during the well operation time. Due to the special type of construction and working feature, ICDs are being called - passive valves. However, the potential advantage of ICD is that the mechanism produces a homogeneous drop of pressure, which equalizes pressure flow at the bottom hole across the horizontal section. Figure 22 shows a schematic example of an oil well completion with and without ICDs, which represents water or gas coning reduction by equalizing distribution of pressure along the horizontal section.

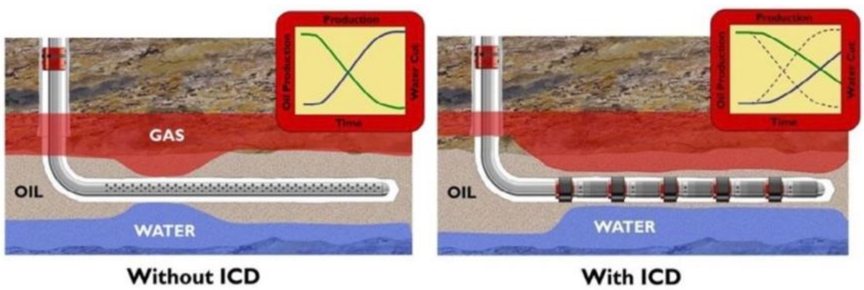

Figure 22: Water and gas front advancement - comparison in conventional and intelligent well

4.3.2 Autonomous passive devices – autonomous ICD or AICD

In comparison with common ICD, the autonomous inflow control devices AICD are moderately the latest breakthrough technology. The (AICD) was designed to neglect the water and gas breakthrough by applying differential density or centrifuge force principle. AICD is a self-regulating fluid flow controlling device able to regulate the fluids flow through internal discs. Figure 23 presents an example of the AICD, with a combined oil and water flow path through the disk (Halliburton 2020 n.d.).

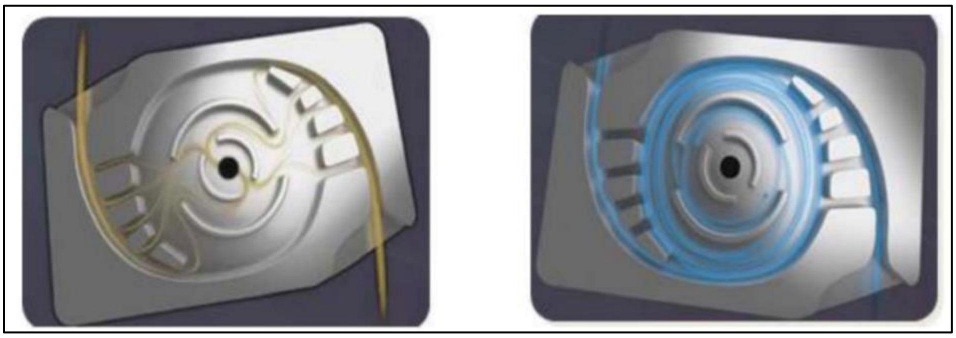

Figure 23: Fluid flow path inside AICD, oil's showed on the left, and the water's on the right (Halliburton 2020 n.d.).

It can be seen that due to the higher density, water flow takes a larger pathway when oil takes a shorter path. The experiment was carried out only in a single phase (Stephen Greci 2014).

4.3.3 Inflow control valves (ICV)

The reactive or actionable valves are considered inflow control devices which valves can be two-positioned (open/closed) or adjustable (throttle valves) with the option to operate on chokes of different sizes, providing more occasions for zone's inflow control. By operation, this ICV can be activated directly by mechanically by spring or hydraulically.

4.4 Applicability of intelligent completion

Looking into the world's best practices, the following example of a multilateral well in Kuwait represents an excellent example of intelligent completion technology that can be used on the YOGC field.

The presence of surface-controlled, variable choke valves to control inflow from both the main bore and the lateral provides the capability to effectively manage the reservoir and production over the life of the well. This, in turn, prolongs the field life, thus improving overall economic performance and field economics. (Arackakudiyil Suresh et al. 2018)

The similarity between the YOGC field and the well in Kuwait's field is that most likely, both wells need the isolation of active zones, and thereby, the convertible TAML level 4 was selected. Moreover, when the well stops producing naturally, the ESP system will be necessary, and the Figure below depicts the well schematic and downhole equipment necessary to have intelligent control over the well. It is important to highlight that this is an example that shows that difference in the well permeability across the lateral wellbore is controlled by the combination of ICDs and swell packers.

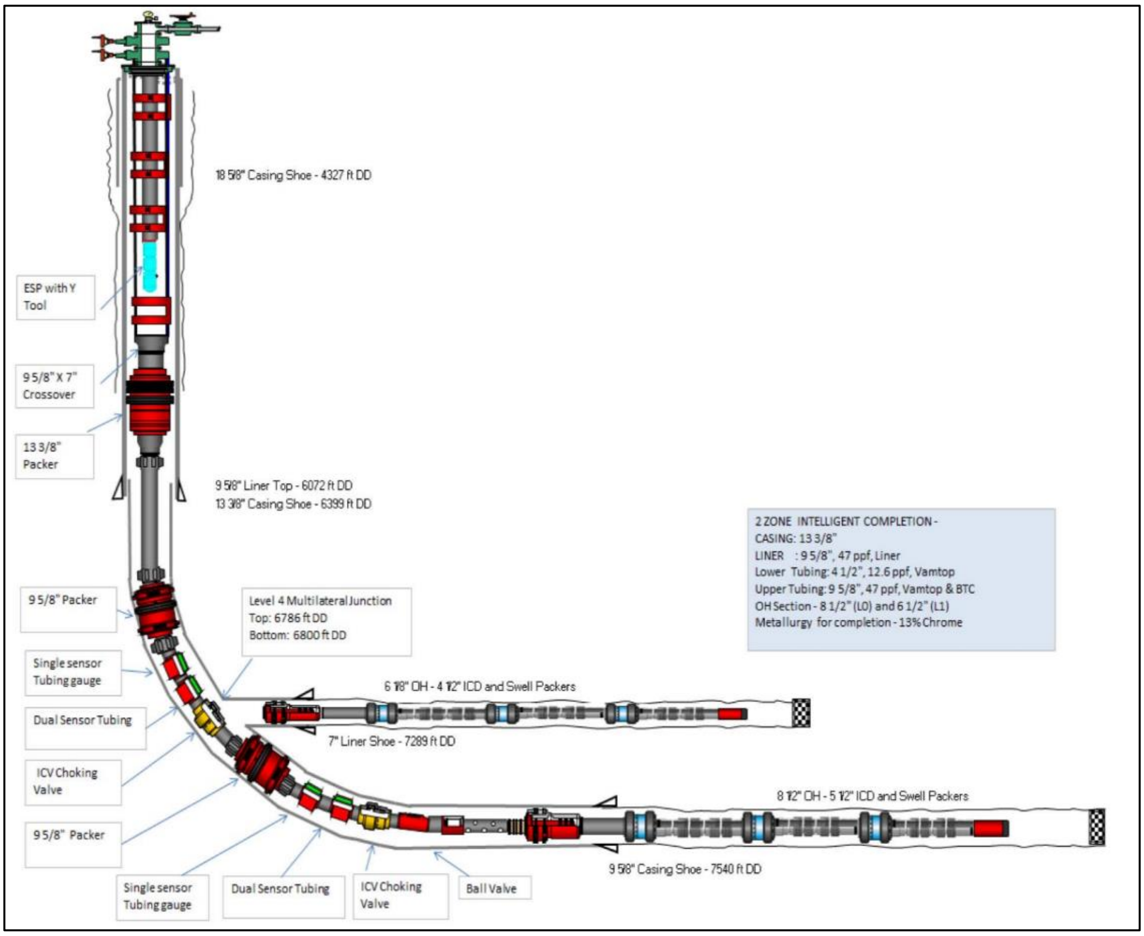

Figure 24: Well Completion Schematic (Arackakudiyil Suresh et al. 2018)

Two ICVs were included in the well schematic to control the commingled production from each lateral and prevent crossflow. Each lateral had different productivity rising from variations in gas/water fractions and difference in the heel pressure. The downhole monitoring system applied to this well allowed immediate reactions and significantly reduced the number of well interventions. (Arackakudiyil Suresh et al. 2018)

5. Selection of Modern Completion Technology

An approach of engineers to completion of well is based on the knowledge of scientific processes and technical means interacting with the external environment. This is impossible without wide application methods of mathematics, mechanics, physical chemistry, geology, geophysics, statistics, drilling, and other sciences. Without a basic knowledge of these certain scientific disciplines, it is unlikely to design wells at a high-quality level and implement a well construction process, and even more, develop completion technology and technique.

5.1 Completion of horizontal wells

At present, in the whole World and Russia, the main wells' completion projects, directed to assure conditions to effectively open productive formations with preserving or increasing its collector properties. Together with this, an essential objective of completion is considered the construction of wellbores' bottom structure, which will allow the company to operate them in complicated conditions caused by instability of collectors, medium corrosion, abnormal pressures, and temperatures, etc. These two directions are mutually connected and have one common goal - provision of optimal conditions of fluid extraction from productive formations. Many different completion designs have been developed over the years and operated for complicated and non-complicated conditions. The most common of these is the design with a production casing being cemented and perforated in the productive formation interval. The simplicity of such technology has led to the fact that almost everywhere, it was the base of the entire well planning design. In international practice, this simple design differed using temperature compensators, packers, etc. However, it has been shown that such an ideal completion design (for olden days) cannot meet the heightened requirements of intensive hydrocarbons recovery from the reservoir.

Additionally, conventional methods of providing reservoir-to-well connectivity during cumulative and gun-fire perforations violate the integrity of the cement sheath behind the column often at a considerable distance from the perforation interval, which causes poor quality isolation of the productive formations. Therefore, bottomhole designs are used that satisfy well operation requirements under specific geological conditions. Thus, in the stable fractured and porous-fractured reservoirs, where projects provide the opening and isolating of productive formation by a cemented casing, due to difficulties caused by fluid losses, the boreholes are often left uncased, or they are cased by perforated tie-back casing equipped with the packers. The practice has revealed the positive and negative features of such a design. Its use hugely simplifies the completion technology, reduces hydrodynamic loads on the bottomhole zone. At the same time, the application of such bottomhole design eliminates the possibility of carrying out the selective well treatment in separate intervals of producing formations.

Currently, the prime task is to create technologies and implement them in the field, which will allow the development of hard recoverable reserves, which are considered unprofitable with current production methods. Gazprom Neft STC was developing this idea with orientation on the Yamburg field since 2014, with the application of horizontal wells (HW) drilling technology and multi-stage hydraulic fracturing (MSHF). Many wells with a horizontal section length of 1000-2000 meters were drilled in the reservoir, and up to 30 stages of hydraulic fracturing (HF) were carried out. The numerous designs, technologies, and HF equipment are used, and development systems with longitudinal and transverse fracturing designs are implemented.

The design of horizontal wells with multi-stage hydraulic fracturing allows multiple increases in the area of drainage of reserves and, accordingly, productivity in comparison with directional wells (oil wells) with hydraulic fracturing. On the southern licensed territory of the Priobskoye field, the following technologies with hydraulic fracturing have been tested by Gazpromneft STC.

- HWs with the horizontal interval length from 400 to 1500 m;
- MSHF with the number of stages from 4 to 30 and proppant mass per stage from 33 to 140 tons, the maximum mass of proppant per well was 1187 tons;
- installation of full bore cemented liners to conduct the initiation of cracks and determining the effect of their number on productivity (11 wells);
- clustered MSHF (about 50 well operations);
- expandable collars;
- reusable couplings for opening/closing the ports (more than 80 wells).

At the beginning of 2017, the number of wells with multistage hydraulic fracturing was about 200 wells, or 14% of the existing active well fund, these wells today provide about 24% of the total daily production of Priobskoye field. The performance of HWs with MSHF is defined by parameters such as length of horizontal section, fracture designs, technologies of multi-stage hydraulic fracturing, and the possibility of additional well stimulation (refracturing). Various types of completion of horizontal wells with multi-stage hydraulic fracturing and multi-stage fracturing technologies were tested in the first year at approximately 50 experimental sites (Listik A.R. 2017). The study of MSHF allowed the company to highlight the technology and engineering solutions that provide greater productivity wells at the Priobskoye field. Due to the unique nature of Achimov formations, the extraction of oil has several features that require the use of MSHF technology for wells completion.

Firstly, productive intervals of Achimov formations have low porosity and low permeability, so before the production stage begins, all intervals must be stimulated with MSHF.

Secondly, horizontal drilling is widely used in gas and oil production in Western Siberia. Although the cost of horizontal wells is one and a half to two times more than the cost of vertical wells, the productivity of horizontal wells is 3-4 times higher than a vertical well.

5.2 Hydraulic fracturing technology

The successful application of hydraulic fracturing in the Petroleum industry began in the USA in 1947. In the USSR, this happened a little later, in 1952. The positive results observed during hydraulic fracturing quickly made them popular in the US oil fields. By the end of 1955, the total number of fractures conducted in American wells have reached one hundred thousand. With the improvement of theoretical knowledge of the process and the improvement of technical features of the equipment used, fracturing fluids and proppants, the success of hydraulic fracturing operations reached 90 percent. By 1968, more than one million operations were carried out in the world. In the USA, the peak in the number of hydraulic fracturing was recorded in 1955 - about 4,500 per month. By 1972, the number of monthly operations was reduced to a thousand, and by 1990 it had stabilized at 1,500 hydraulic fracturing operations per month. The peak occurred in 1958–1962 when the number of operations exceeded 1,500 per year. (Sofia Zorina, Kirill Nikolaev 2015) The technological key for commercially efficient recovery of hydrocarbons from low permeable and low porous formations as argillites with sandstones interlayers is hydraulic fracturing. It involves injecting high-pressure fracturing fluid with proppant into the formation to create cracks or expand natural cracks in the formation thicknesses. The HF improves permeability, decreases the resistance of fluid flow, improves well's surface filtration, and finally increases hydrocarbons production. In the development of poor-permeable formation, HF has become an effective and important supplementary operation for the completion of horizontal wells. The HF method has many technological solutions due to the peculiarities of a particular processing well and an achievable goal. According to the type of stimulation fluid, fracking technologies are divided into gel-based HF, water-based HF, hybrid HF, foam-based, and anhydrous HF. By a procedure of carrying out a fracturing process, it can be divided on hydro jet-assisted HF, multistage HF, simultaneous HF, repeated HF, and HF with the creating open channels. HF classification based on stimulation fluid and the execution technology is presented in Tables 18 and 19. (Luca Gandossi 2013)

Table 18:HF classification based on stimulation fluid.

Fluid type	Specialty	Application area
Gel-based HF	High sand-bearing capacity; strong formation damage.	Water-sensitive and plastic formations.
Water-based HF	Low cost; smaller contamination; possibility to form complex cracks.	Formations with developed natural cracks; high fragility rocks.
Hybrid HF	Possibility of using a large volume of proppant and obtaining longer effective cracks; less formation damage; less hydraulic loss.	Formations with developed natural cracks; in groundwater presence.
Foam based HF	Low formation damage; less fracturing fluid loss; high sand-bearing capacity.	Water-sensitive formations or/and at a depth less than 1500m.
Anhydrous HF	High diffusion coefficient; the low-pressure boundary of formation fracturing; environmentally friendly.	Highly clay formations or/ and with high capillary pressure.

Table 19: HF classification based on execution technology

Hydrojet HF	Mechanical insulation is not required; precise localization; Accelerates and simplifies fracking works; economically profitable.	At completions with uncased bottomhole
Multi-stage HF	The possibility to fracture many formation intervals; the allocated fracking; mature and widely used technology.	Multilayered productive formations; Horizontal wells with long horizontal section.
Simultaneous HF	Simultaneous fracture of several wells amplifies interactions; complex networks of cracks are formed; saving operational time	The high density of wellbores; parallel location of horizontal wells;
Repeated HF	Recovery of fracture conductivity and well productivity; reorientation of fractures.	Old wells; wells with reduced productivity.
Channels opening HF	Not continuous stuffing of proppant; the possibility of creating a network of discrete open channels, an increase of cracks' conductivity.	The relationship between Young's modulus and crack closure stress is above 350; heterogeneous distribution of perforations.

In North American practice, the two essential technologies providing industry profitable development of low permeable oil and gas fields are water-based and multi-stage hydraulic fracturing. In Western Siberia of Russia in low permeable and low porous (like Achimov) formations with similar properties of rocks, key technology became multistage hydraulic fracturing.

5.3 Multi-stage hydraulic fracturing

Multistage fracturing (Multistage Fracturing) is the key to the success of the shale revolution in the United States and is used in the completion of horizontal wells mostly, allowing to increase the area of contact with the productive formation. Since the beginning of 2011, most of the wells put in operation by Gazprom Neft are horizontal wells with multi-stage hydraulic fracturing (MSHF) Figure 25.

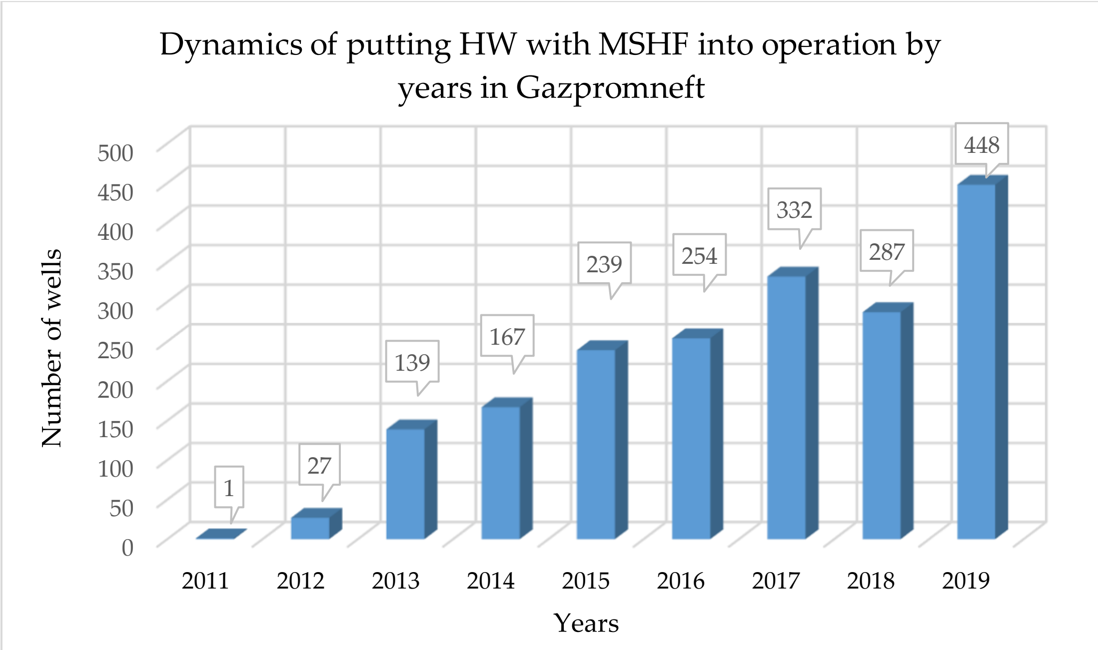

Figure 25: Horizontal wells with MSHF put on operation over years in Gazpromneft.

Currently, over 2700 wells with hydraulic fracturing have been drilled at the company's fields, equipped with non-cemented packer-port liner assemblies, which are being activated by the ball-drop technique, approximately 800 wells out of them are equipped with single-acting hydraulic frac sleeves (K.V. Kulakov, S.V. Tishkevich 2019).

In 2018, a striking event took place in the oil and gas industry of the Russian Federation. For the first time in the industry, since 2014, the volume of production wells in the country did not increase compared to the previous year, but on the contrary, it decreased by more than 3%. At the same time, the introduction rate of more technologically complex horizontal wells continued to grow and increased by almost 21%, from 2,974 wells in 2017 to 3,587 wells in 2018. Meanwhile, the number of directional wells decreased by almost 14%, from 5955 wells in 2017 to 5104 in 2018. According to the same scheme, the hydraulic fracturing market developed last year by 14%. The number of low-cost single-stage hydraulic fracturing operations decreased by 7.5% compared to the previous year, while the number of expensive multi-stage hydraulic fracturing operations (MSHF) increased by 41% (ROGTEC 2019).

According to the report, there is a tendency to displace cheap low-efficiency technologies by more expensive technologies. More effective technology like MSHF can become long-term in the Russian oil service market. As is Multi-stage hydraulic fracturing is one of the common methods of intensification of hydrocarbon production in deposits with low-permeable collectors. The technological criteria of MSHF efficiency are the sufficient increase of well production rate in the result of its application. The success of multi-stage HF during the development of oil and gas deposits depends on the optimal design of horizontal sections of wells. For example, wells must be drilled perpendicular to the maximum compressive stress, penetrating structural complications must be avoided, etc. The multi-stage hydraulic fracturing, despite the high cost of the operation, has a serious economic justification. Characteristics of multi-stage hydraulic fracturing are the ability to break multiple formation intervals, localized fracturing, high efficiency of action on formation, etc. This method is most suitable for the treatment of multi-layer deposits since the oil content in Achimov layers is different; the use of multi-stage hydraulic fracking can fully solve this problem.

5.3.1 Geometry parameters and fractures propagation in HF

The development of formations with low-permeability requires a reticular fractures system to maximize well productivity. In traditional reservoirs, very often, simple hydraulic cracks are formed, having the shape of bird wings in the plane projection. Half-length and the conductivity of these cracks are key indicators for evaluating stimulation effectiveness. In low permeable shale collectors, where complex three-dimensional networks of cracks are being created, the half-length and conductivity of cracks are insufficient for describing the efficiency of the stimulation. The concept of volumetric HF has only emerged in recent years, to describe the difference between shale treatment and traditional collector treatment. The formation volume affected by hydraulic fracturing, the effective permeability of the formation, and well productivity are increasing. To implement the volume treatment, the cluster perforation, and the crack reorientation technology are often used. Low viscosity fracturing fluid, smaller proppants, and materials to control fracture reorientation are commonly used as fracturing materials. During the HF operation, a large volume of fracturing fluid is consumed to force the creation of not only the main cracks, but also the secondary cracks due to the shear, sliding, crossing, and other effects (Figure 26). Secondary cracks continue to extend and are forming branched cracks (C. Pin., V. S. Yakuwev n.d.).

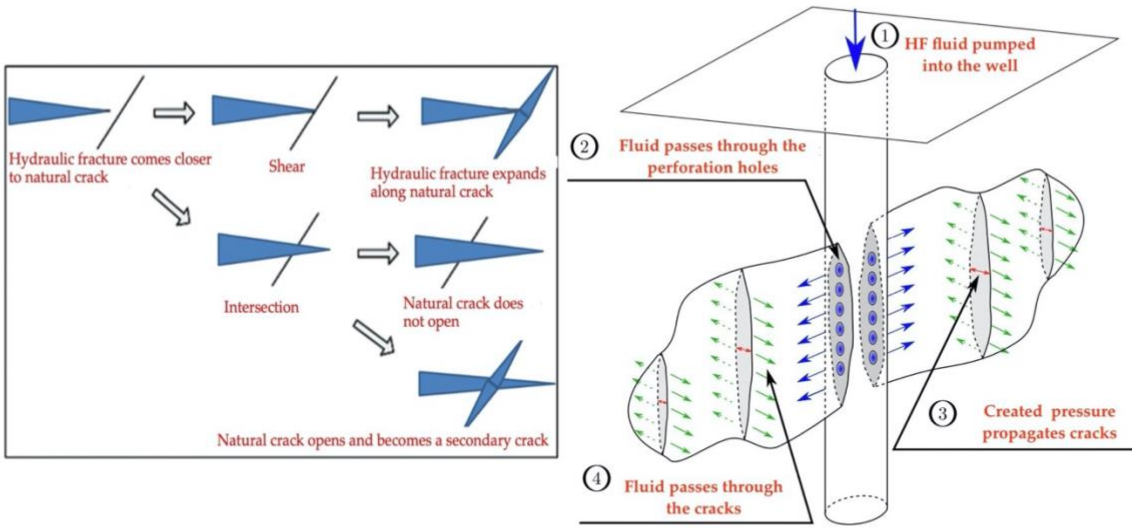

Figure 26: Cracks propagation process

During the perforation of traditional deposits, the main attention is paid to increasing the density of holes, penetration depth, and coverage of the interval. When operating unconventional deposits in which it is advisable to limit the perforation interval, including for the exploitation of gas shale strata, this approach cannot be applied. Selective perforation of shales consists in the creation of several groups (clusters) of perforations or single holes distributed over large intervals. Perforation with the creation of clusters of perforations is used when performing multi-stage hydraulic fracturing.

Clusters can be spaced or concentrated near intervals with optimal reservoir and completion quality (Figure 27).

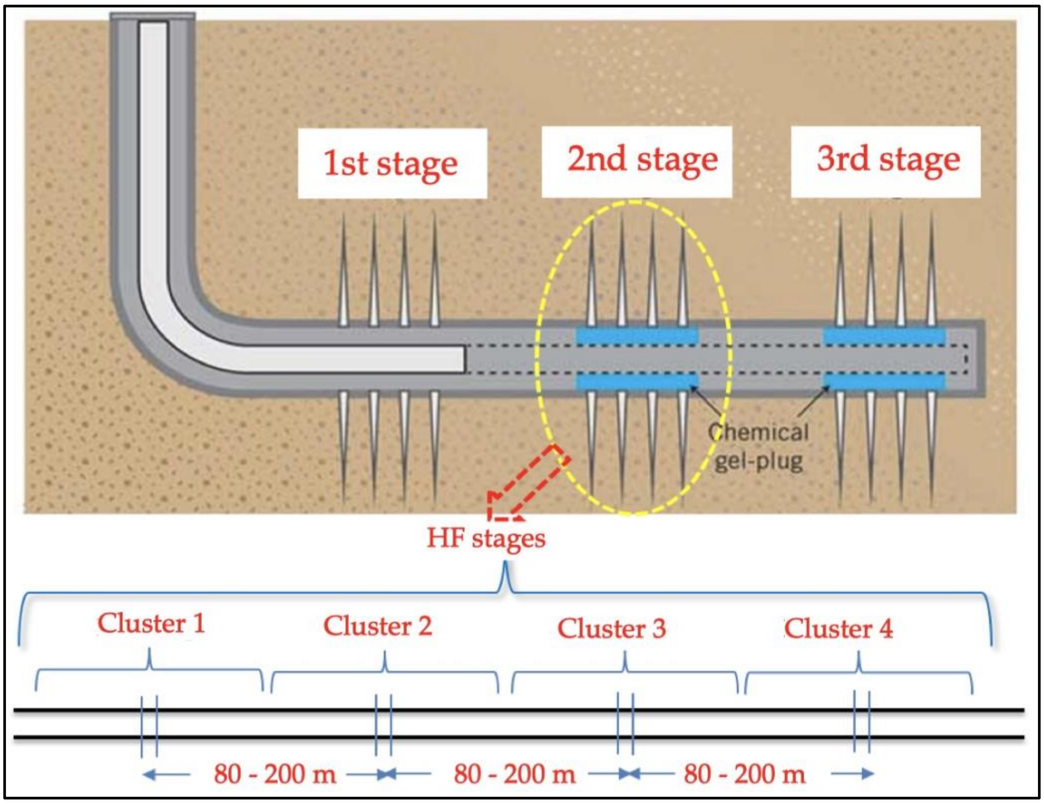

Figure 27: Illustration of cluster perforation in the design of multi-stage hydraulic fracturing (C. Pin., V. S. Yakuwev n.d.).

5.3.2 Optimizing number of stages and design of HF

In the main part of the wells at the Priobskoye and Yamburg field, cracks are located along the wellbore, which is due to the chosen development system. For such horizontal wells knowing the half-length of the crack, it is possible to calculate the required distance between the ports based on the condition of the cracks. However, in practice, this theory has not been fully confirmed. According to the study of Gazprom Neft STC specialists (Listik A.R. 2017):

- For wells with an average proppant volume of about 70 tons and half-length fractures in designs of about 120 m, the optimal number of HF stages is on average recorded at a port spacing of about 125 m;
- For wells with an average proppant volume of 120 tons per stage and half-length fractures in designs of about 150 m, the optimal amount of HF stages is, on average, designated at about 150 m port spacing distance.

Table 20 shows the geological and technological parameters of MSHF performance in the two-neighboring horizontal test wells at Priobskoye Field. Figure 28 and 29 shows the simplified history of fluid production from these two wells.

Table 20: Geological and technological parameters of MSHF performance in two neighboring HW in the tested site at Priobskoye Field.

Indicators	Well X	Well Y
Formation thickness, (m)	14,2	19,5
Permeability, 10^{-3} mkm²	0,3	0,4
Length of horizontal section, (m)	774,2	744,5
Number of HF stages	6,0	4,0
Distance between ports, (m)	129,0	186,0
Proppant weight for the per stage, (t)	70,2	93,5
Per 1 meter of formation, (t/m)	5,0	4,8

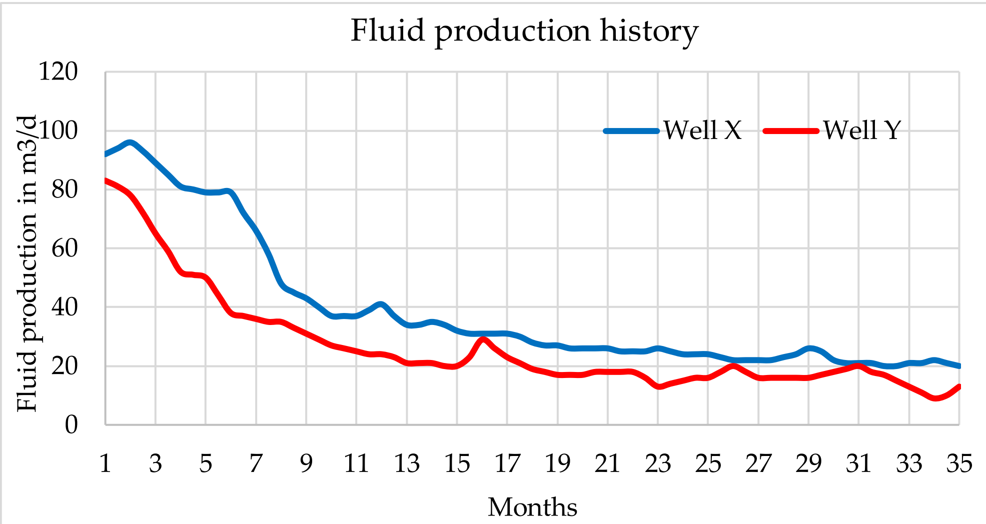

Figure 28: flow rate of experimental wells in [m³/days]

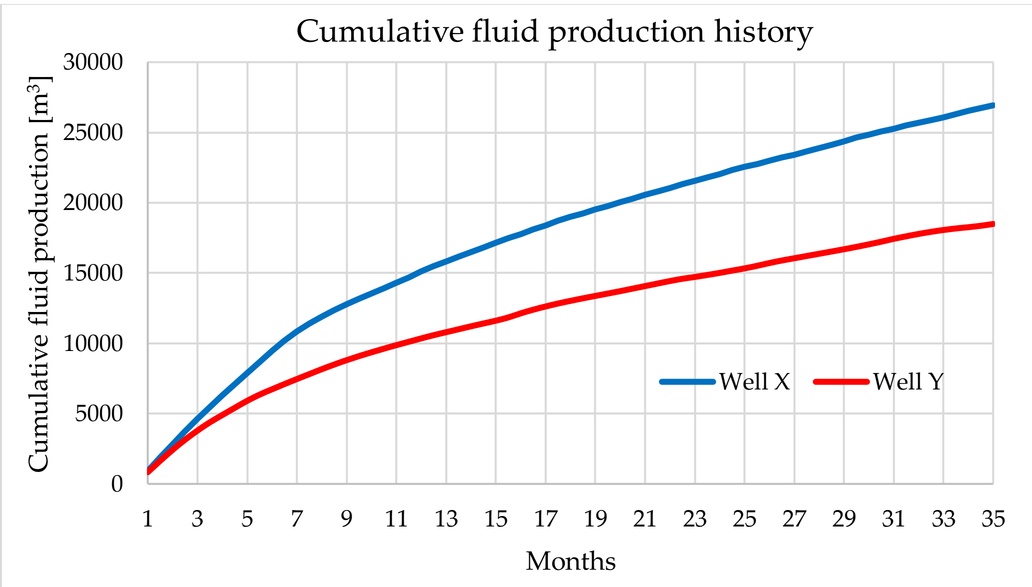

Figure 29: Cumulative oil production [m³]

Additional experiments were carried out on test sites in neighboring wells in which the distance between ports varied from 50 to 200 m, and various mass of proppant per stage was used. When increasing the number of stages and reducing the distance between ports less than 100 m (cracks along wellbore), there was no increase in well productivity. Another experiment was conducted in two neighboring wells of the well cluster № 130, in which, with the same reservoir properties and the length of the horizontal section, the number of stages and the weight of proppant per stage were different: 18 stages with 50 tons per stage, and eight stages with 80 tons per stage, respectively. In the latter case, oil production for eight months of operation was 4% more (Figure30).

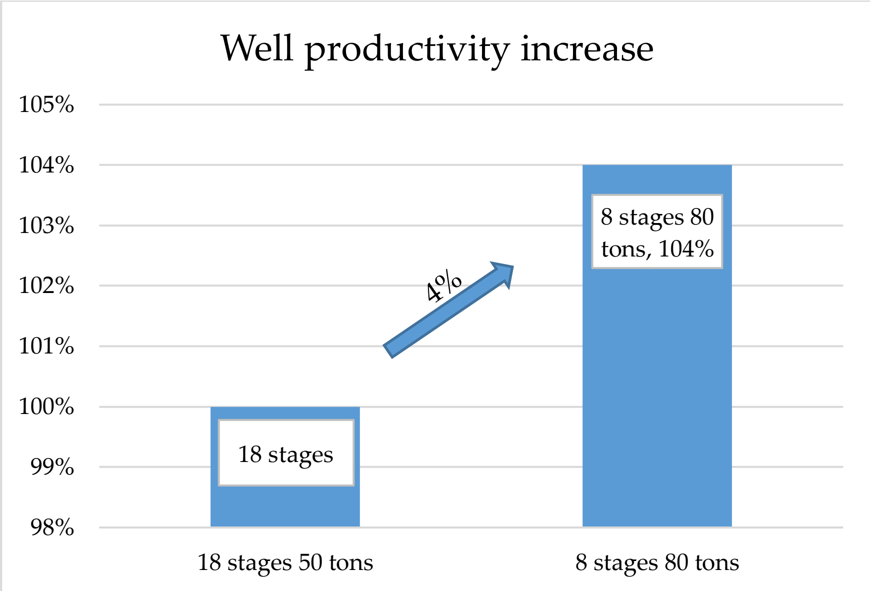

Figure 30: Experiment with proppant volume and stages change

It should be noted that the increase in proppant mass significantly effects on well productivity. In the tested wells, increasing the mass of proppant from 70 to 100 tons at the comparable thickness and reservoir properties of the formation, lengths of horizontal sections, and the number of stages of MSHF allowed to achieve an increase of accumulated production up to 30%. In low-permeable collectors, the creation of longer fractures, especially at the endpoints of the HW, makes it possible to increase the area of coverage of the formation by the hydraulic fractures and accordingly increase the productivity of the well. Thus, to increase the efficiency of HS with MGRP in the absence of geological limitations, it is necessary to create longer cracks, which will increase the area of drainage of reserves (Listik A.R. 2017).

5.3.3 Refracturing possibility and recommendations

Over the producing time, under the influence of different geological and technological factors such as removal of mechanical impurities, -plugging of perforation and frac sleeves intervals by sand or proppant can be caused by the formation of asphaltene deposits, salt, etc. There is a gradual decrease in the productivity of such wells. Today, one of the intelligent solutions for improvement of oil recovery is repeated stimulation of the horizontal section with MSHF, which is one of the urgent tasks of Gazpromneft specialists.

This technology allows reorienting the azimuth of the fractures. The extraction of the formation fluid using hydraulic fracture heads to a local change in reservoir pressure. The drainage area takes the shape of an ellipse along the generated hydraulic fracture. The reduction of reservoir pressure in this zone causes a decrease in the maximum horizontal stress (parallel to the created fracture) faster than the minimum. If the pressure changes are large enough, then the initial direction of the minimum horizontal stress becomes the new direction of the maximum stress inside the elliptical zone of reduced reservoir pressure. Then the development of new hydraulic cracks will occur perpendicular to the direction of the original ones. Upon reaching the boundary of the depleted zone, the secondary crack will change its direction by 90 degrees (Figure 31).

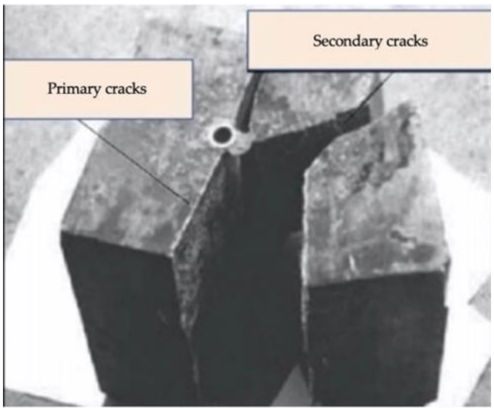

Figure 31: Initiation of secondary cracks at refracturing.

The expected growth of the Horizontal wells with MSHF drilled by Gazprom Neft in Russia by 2030 is over 2700 wells (Listik A.R. 2017). Considering the Gazprom Neft STC statistics obtained from the directional and horizontal wells with HF, it will be necessary to carry out more than 700 repeated MSHF to maintain the target levels of oil production. In low-permeable collectors (less than 0.2-0.3 μm^2) the traditional development system with reservoir flooding and drilling of horizontal wells with the longitudinal location of cracks is no longer effective. To involve hard-to-recover reserves in the development Gazpromneft in early 2017 has constructed three wells in which cracks were located perpendicular to the horizontal section of the well. A complete set of geophysical and micro-seismic studies has been carried out. Based on the results of these works, the development of new previously unavailable hard-to-recover reserves could be planned. Thus, the identification of the best technological solutions with confirmation of theoretical justifications by pilot-field tests allows planning the development of oil reserves, which were previously considered unprofitable.

Main reasons for hydraulic refracturing:

- Cases of early injection termination (alerts) and other scenarios with deviations from the planned program;
- Stimulation through the fracking ports skipped during the first treatment procedure.

Main recommendations for carrying out hydraulic refracturing at the following situations:

1. Formation pressure is not lower than 0.6 of its initial value;

2. Percentage of water cut not more than 80 %;
3. Remaining reserves more than 5,000 tons;
4. Skin factor higher than - 3;
5. Rock barriers at least 15 m thick separating water- and gas- saturated sublayers;
6. The remoteness of productive zone from the water-injection front;
7. Presence of intervals that have not been stimulated during the first-fracturing.

In the fact, the technological problem of refracturing is that the typical design of wells (single-use ball activation assemblies in the liner for MSHF) does not provide for repeated hydraulic fracturing, which creates difficulties in the selection of technologies:

- impossibility to manage ports;
- lack of the opportunity for selective processing of the interval without the use of additional technologies;
- the impossibility of predicting the point of initiation and the direction of the secondary crack;
- the presence of intervals narrowing the diameter of the liner.

There are two ways of further technology development: the selection of technologies of repeated HF using existing assemblies and selection of alternative methods of wells' completion. Currently, oil services in the field of HF offer quite many technologies and approaches to carrying out MSHF (refracturing). They all deserve attention, but the question arises whether they are all workable and universal or not (K.V. Kulakov, S.V. Tishkevich, 2019).

5.4 Selection of completion technology for multilateral well

This chapter will discuss various modern technologies of well completion with MSHF. The main criteria of selection and comparison are costs, possibility to carry out repeated HF, the feature of technology, and its availability on the market.

5.4.1 Conventional plug and perf completion systems for MSHF.

The method of intensification is often used, called on industry jargon "plug-and-perf". After the well has been drilled and cased, a perforation system is lowered into the casing or open hole wellbore up to the end of the well. Perforation and fracking operations are carried out at the first stage from the bottomhole to up. Then in the production casing/liner at the near boundary of the treated interval, a temporary bridge plug is installed that isolates the perforated interval from the rest of the well. Then the same perforation and fracking job are performed at the second interval separated from the first one by the plug, and the second plug is installed. These operations can be repeated many times until the entire horizontal section is perforated and fractured. The main advantage of plug and perf technology is that the whole process of MSHF is carried out exclusively using the wireline equipment and hydraulic fracturing unit. Thus, it is no longer necessary to involve the workover crew to carry out tripping operations. This technology can be carried out by coil tubing, soluble balls, and on a wireline. Which increases the possible application scenarios in different field situations and partially affects the price and operation time. Example of plug and perf completion assembly on CT shown in Figure 32.

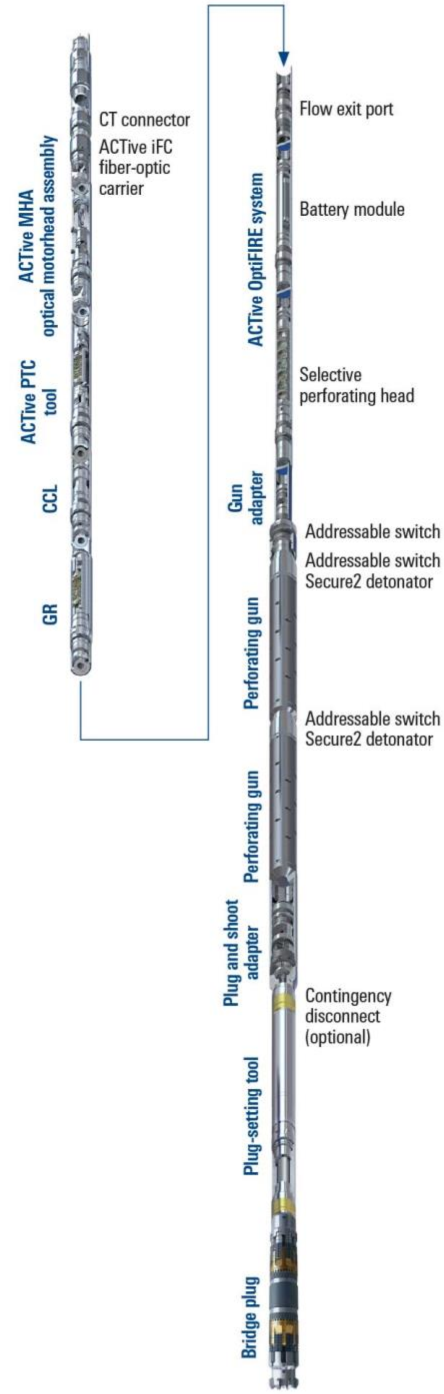

Figure 32: “ACTive” Plug and Perf completion assembly on CT (Schlumberger 2019)

5.4.2 Ball-activated completion system for MSHF

Application of completion equipment with MSHF couplings allows us to carry out multi-stage hydraulic fracturing without additional in-hole operations. When using the ball-activated completion system, a liner with circulation couplings and an annular packer system for isolating intervals is lowered into the horizontal part of the well. The liner, equipped with couplings with opening ports, is initially tight and does not allow communication between the inner space of liner and the annular space. During the operation, balls of calibrated size are dropped into the fluid flow and according to the principle of a Matryoshka doll, starting from the smallest ball diameter, closing the ball valve seats in couplings from bottom-up. The increase of pressure opens ports, providing communication with the formation for further operations. Thus, at the end of each stage of hydraulic fracturing, the ball dropped into the well isolates the previous interval and opens the ports in the liner opposite the next processing interval, which allows forming the planned number of clusters along the horizontal part of the wellbore. Besides, the couplings can be closed and opened again to be suitable for multi-use operations. Completion systems with couplings by equal efficiency can be used in horizontal, vertical, and deviated wells. Due to such options, it is possible to optimize the location of the start points of the MSHF or to block the flow of fluid after stages of hydraulic fracturing. This technology can be carried out using composite and soluble balls. Composite balls were pioneers of this technology and in the usual case are infrequently used due to the extra operational time for drilling through ball-seats, and the inability to carry out the refracturing.

The use of soluble balls greatly simplifies the multi-stage fracturing process, reducing the time and overall operating cost. After completion of the MSHF operation, the ball made of composite material had to be drilled through to perform repeated hydraulic fracturing. Soluble balls exclude this stage, reducing the time required to lower the equipment into the well and performing multi-stage fracturing. Such balls are made of magnesium and aluminum alloy with the addition of alloying additives. Picture of the soluble ball presented in Figure 33).

Figure 33: Soluble Ball for coupling activation in MSHF

At the same time when interacting with gels and fracturing fluids for MSHF, the balls completely dissolve. The magnesium-aluminum alloy will take 15-20 hours to dissolve depending on the aggressiveness of the solution, and the composition of the ball. After this, the inner space of coupling opens and it becomes possible to proceed to the next stage of the work (Wan 2011).

5.4.3 Full-bore frac sleeves activated by coil tubing for MSHF

In the modern completion realities of Russia and all around the world, completion operations by application of liners with HF assemblies are enlarging popularity. Openable/closable ports, assemblies with full-pass crossing section controlled by coil tubing allow to carry out selective multistage hydraulic fracturing on both, new wells, and wells with productivity reduction after some period of operation, develop and bring inflow to each productive interval separately and simultaneously. A Special key is used to open/close the HF ports. Operation with the HF ports is carried out using the full-bore coil tubing activated frac sleeves, and lifting sleeve before every fracturing operation is not required. HF is carried out behind the annular space of coil tubing. An additional advantage of this technology is the possibility to add new fracturing stages to the already installed system using hydro-sand-jet perforation. MSHF completion technology with full-bore coil tubing allows carrying selective hydraulic refracturing operations, as well as to selectively open and close HF ports in case of water and/or gas conning. Another good side of technology is the reduction of operation time for putting well into operation, which accordingly, reduces financial costs. This eliminates the need to drill seats/balls, allows the borehole circulation without additional tripping in and out operation of string, while the full-bore size inner diameter of the assembly excludes restrictions on further downhole operations, and makes possible to carry out MSHF on wells with controlled ports in any sequence. There are no limitations on the number of HF stages in the well. The technology allows efficient extraction of hydrocarbon reserves due to multiple increases of fractures contact area, control of cracks initiation zone, size, and conductivity. This technology makes it possible to design 114 mm (4 1/2 in.) combined production liner, with casings in the upper part, and with the installation of hydraulic fracturing ports at the bottom of the liner. This may be one of the main technologies for wells' completion at the Achimov formations of Yamburg filed with a reduction of operations time. However, there is a question about the cost of technology and how profitable it will be or not. MSHF procedure is described below, using the example of "Precision Completion" technology from the Schlumberger.

The design of the "fracturing (sliding sleeve)" assembly is shown in Figure 34. The system expressed as a 114 mm (4 1/2inc) liner lowered by a drilling string into the open bore of 152.4-155.6 mm (6 - 6 1/2 in.) from a production casing/liner of Ø177.8 mm. The liner includes an upper packer with a polished funnel for the stinger, hydraulic liner hanger, fracturing sleeve couplings, an activation clutch, and float shoe.

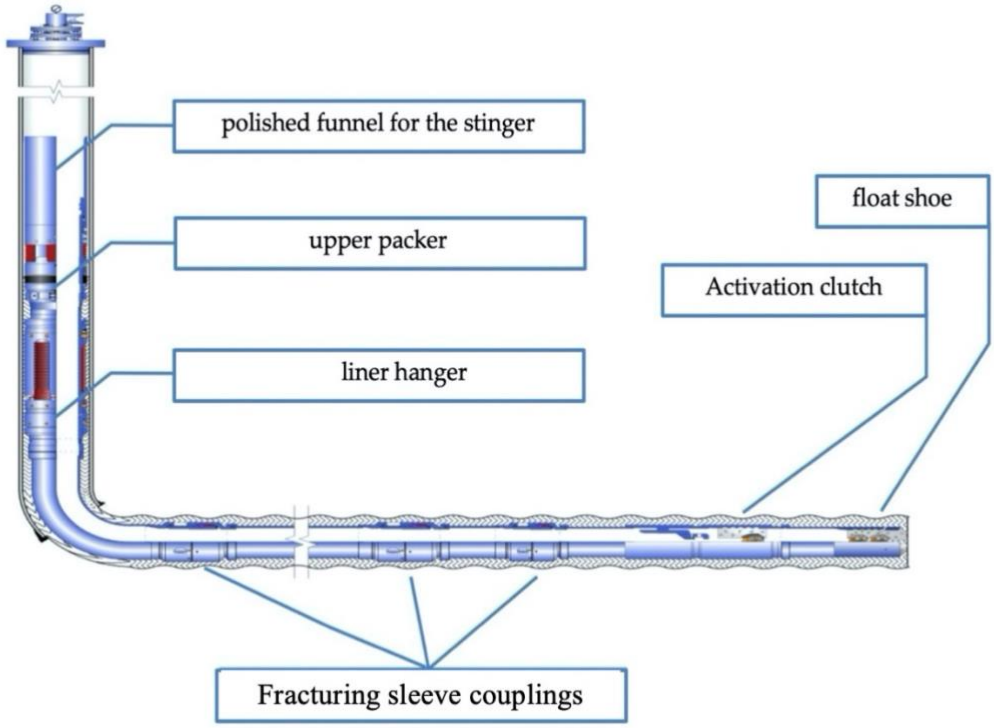

Figure 34: Scheme of 'Precision completion sleeves' system (Schlumberger n.d.)

When the CT with completion assembly in the bottom part is lowered, fracturing sleeve couplings are closed, so it is possible to perform well circulation through the shoe. The scheme with operations order is shown in Figure 35.

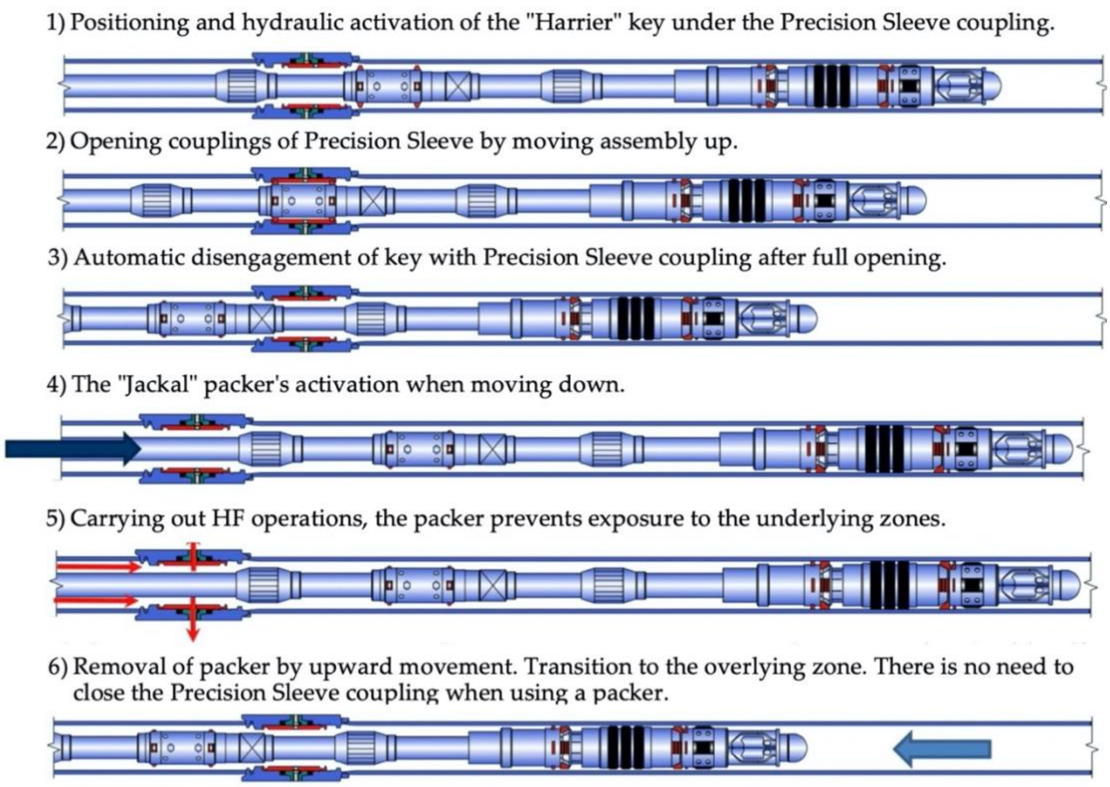

Figure 35: Operation Scheme of "Precision Frac sleeve" (Schlumberger n.d.)

Before carrying out HF, coil tubing with a key and a packer goes down. The "Harrier" key is located 3-5 meters below than the lower Precision Sleeve coupling and activated by pumping fluid through coil tubing, at the same time the created internal pressure extends the pawl key from the body. The activated wrench moves up with the coil tubing and its pawls engage the internal sub of the Precision Sleeve coupling. Further upward movement of the key moves the sub, thus opening the sleeve. Reaching the extreme upper position, the key rests with its pawls to the mutual shoulder of the coupling body, and the pawls are pushed into the key body, thus automatic disengagement of the key and coupling takes place. Thereafter, the pumping of the fluid through the coil tubing is stopped and the key is deactivated. Unlike mechanical keys, the hydraulic activation system of the "Harrier" key allows us to open and close an unlimited number of Precision Sleeve couplings with the same key. After opening the coupling and deactivating the key, it is positioned below the Precision Sleeve couplings. After that, the fracturing operation is performed in the annulus (K.V. Burdin, M.A. Demkovich n.d.).

5.4.4 Burst ports systems (BPS) for MSHF completions

The innovation technology was developed by the company "Trican Well Services" LLC. The company proposed to use BPS systems for well's completion with MSHF, which activates when the pressure reaches a certain level. A large range of burst pressure systems was developed for use at the Samotlor field in the Russian Federation. BPS couplings can be separated by annular packers and used both in cemented and uncemented liners/casings. As can be seen from Table 21, there are many options for manufacturing BPS and their combination for specific tasks is possible. Since the BPS are part of a standard liner/casing, there is no need for large capital expenditures on expensive wells' completion equipment.

Table 21: Parameters of Burst Port Systems BPS.

Casing			Liner			Burst port system (BPS)			
OD, (mm)	ID, (mm)	Weight, kg/m	OD, (mm)	ID, (mm)	Weight, kg/m	Type	L, (m)	ID, (mm	OD, (mm)
139.7	124.3	25.1	101.6	88.6	15.34	Non - Cemented	0.5	80	114.6
146.1	130.7	26.2	101.6	88.6	15.34	Cemented	0.7	83	117.8
146.1	130.7	26.2	101.6	88.6	15.34	Cemented	0.55	83	117.8
146.1	130.7	26.2	101.6	88.6	15.34	Non - Cemented	0.5	83	117.8
146.1	130.7	26.2	101.6	88.6	15.34	Cemented	0.7	88.6	123.8
146.1	130.7	26.2	101.6	88.6	15.34	Cemented	0.55	88.6	123.8
146.1	130.7	26.2	101.6	88.6	15.34	Non - Cemented	0.5	88.6	123.8

Casing			Liner			Burst port system (BPS)			
OD, (mm)	ID, (mm)	Weight, kg/m	OD, (mm)	ID, (mm)	Weight, kg/m	Type	L, (m)	ID, (mm	OD, (mm)
168.3	150.5	35.1	101.6	88.6	15.34	Cemented	0.55	88.6	132.9
168.3	150.5	35.1	101.6	88.6	15.34	Cemented	0.7	88.6	132.9
168.3	150.5	35.1	101.6	88.6	15.34	Cemented	0.5	88.6	132.9
168.3	150.5	35.1	114.3	99.5	19.4	Cemented	0.7	99.5	133.5
168.3	150.5	35.1	114.3	99.5	19.4	Cemented	0.5	99.5	133.5
168.3	150.5	35.1	114.3	99.5	19.4	Cemented	0.5	99.5	133.5
177.8	159.4	28.2	114.3	99.5	19.4	Cemented	-	99.5	133.5
168.3	150.5	35.1	168.3	150.5	35.1	Cemented	-	150.5	205

The difference between cementing and non-cementing couplings is only in the flanges and grooves for better cement passage and reduction of the cement slurry cake over the membranes. Couplings consist of a steel billet with membranes installed in specially prepared holes, which are adjusted to operate at a certain pressure. When this pressure is created, the membranes break and open the channels for hydraulic fracturing. Thus, the BPS technology allows selecting the pressure required for operation in the well and at which these couplings will not open inappropriately before the operation. The opening mechanism itself works as follows: since the couplings operate from designed pressure, it is necessary to consider the hydrostatics of the fluid column. For instance, the coupling is designed to operate at 456 Bar, we take a safety margin of 80% and subtract the hydrostatics of 172 Bar, and remain 192 Bar - this is a pressure that, without exceeding, it is possible to carry out the in-well operation without risks for premature activation of the BPS. When we increase the pressure above 192 Bar, the membranes instantly open. The non-cemented and cemented BPS are presented in figures 36 and 37.

Figure 36: Non-Cemented Burst Port System (BPS)

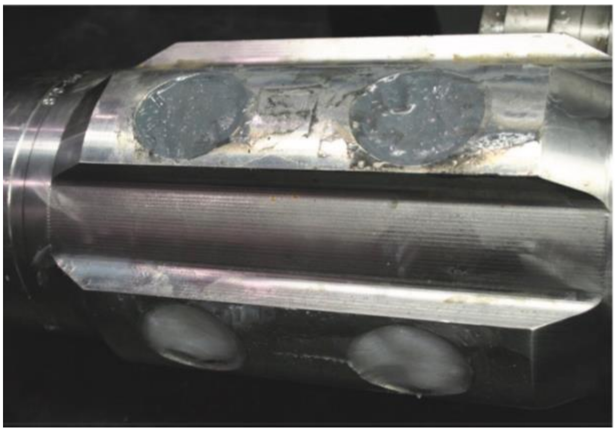

Figure 37: Cemented Burst Port System (BPS)

In addition to BPS, it is suggested to use a cup to cup (C2C) packer, which can be installed only for 114mm and 168mm production casing/liner. This special tool designed to seal all subsequent and previous intervals from the target interval and perform hydraulic fracturing, acid treatment, and cementing. Accordingly, for MSHF, operations should be performed with BPS + C2C packer combination (Kudrya 2015).

The cup to cup packer (C2C) shown in Figure 38 and consists of:

1) The disconnector - used to connect this packer to the coil tubing or drill string.
2) Spring centralizer - to stiffen the tool when passing through the column.
3) Upper cups - necessary to seal the annular space.
4) Rigid centralizer - carries all the weight of the assembly when lowering down the column.
5) A Fracking port - agent is pumped through this port into the well.
6) Lower cup - necessary to seal previous intervals.
7) Diverter valve - at a certain flow rate and pressure are created, it closes and activates the cups, at the same time the pressure between the cups increases before the couplings are opened. After the pressure is released, it opens.
8) Mechanical coupling locator - necessary for correct positioning of C2C packer on BPS couplings, during installation
9) Set of powerful magnets - necessary to capture metal shavings during running.
10) Guide shoe - allows the tool to enter the liner.

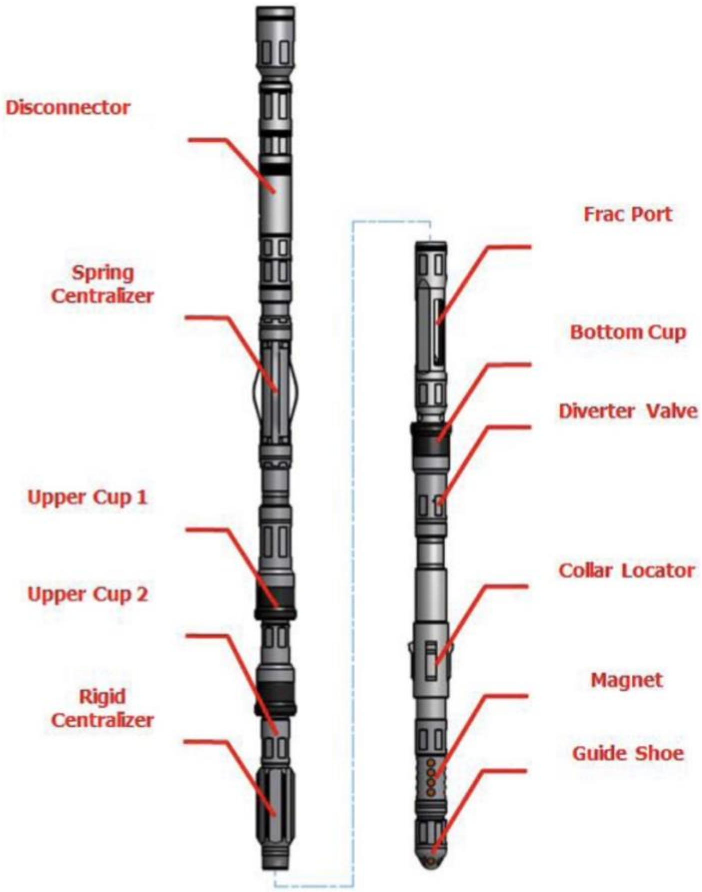

Figure 38: Scheme of Cup to Cup (C2C) Packer, (Kudrya 2015)

The technology looking promising, but the question arises as to whether it is effective and whether the instrument responds without any errors during operations, and economic analysis and comparison are also needed to understand the benefits of the method.

5.5 Summary of technology comparison and selection

This chapter will provide a brief technical and economic analysis of technology selection and comments. The technologies and the main comments to be taken into account are given below in Table 22. Information about cost equivalency was provided form the technological session of Gazprom Neft STC (Philipp Brednev 2018). For the notion of how much the prices of the given technologies differ, they have been displayed in proportion.

Table 22: Completion Technology selection and comments.

Technology	Cost equivalency	Refracturing possibility	Disadvantages / Comments
Ball-activated systems	X	yes	1. Limitations with stages 2. Limitations with proppant volume; 3. May requires drilling through ball-seats (extra time + money expenses) 4. Erosion of ball-seats, in case, if they will not be drilled through.
Full-bore frac sleeves on CT	1.17X	yes	1. Proppant volume restrictions; 2. Issues with CT reaching bottom;
BPS couplings with CT	1.5X	yes	1. Proppant volume restrictions; 2. Requires the flow back period which is extra time;
Plug and Perf on wireline	6.6X	no	1. Setting plug before operation; 2. Requires CT operations and crew for drilling through plugs, (extra time + money expenses)
Plug and Perf on coil tubing	8.5X		1. The limitation with controlling stages and flow regulations;

The ball-activated systems may be one of the simplest, however, they are mainly reserved for use in wells with a small horizontal section where a limited amount of HF is carried out. According to the field data of first horizontally drilled well at the YOGC field, with the Ball-activation system it was impossible to carry out more than 10 stages of Multi-stage hydraulic fracturing. To continue completion of the well, the company had to incur additional costs for attracting service companies and for carrying out the last 8 stages of hydraulic fracturing. The choice of this technology does not fit Yamburg’s specifics due to the long horizontal section of designed wells, where it is necessary to carry out MSHF with a large number of stages than the technology can offer.

One of the specifics of Achimov formations is the very negative influence of well-killing operations on the wells' productivity. According to completion experience at Achimov formations, the productivity of wells can drop by up to 50%. Burst Port Systems is one of the recommended technologies that could be applied in completion operations at Yamburg, but due to the necessity for well’s flow back period, this method is not recommended. Every stage of HF will require to shut down the well, which could not only have a negative effect on productivity but also increase operation time.

Plug and perf hydraulic fracturing system is one of the simplest completion solutions for MSHF and is widely used in many projects where the possibility of repeated HF is not taken into account. As the project of drilling horizontal wells in the YOGC field is important for the company, it is necessary to take into account the possibility of repeated HF. The technology of full-bore frac sleeve activated by CT can carry out repeated HF as well as manage ports, though it also has its argument for fulfillment. The argument is that it is necessary to use a CT diameter of 60.3 mm (2 3/8 in.). Pipes with this diameter are not available in the Russian service market, and therefore it is necessary to develop a plan for the import of pipes with this diameter. The second question relates to the weight of the CT reel. In consequence, this reel with equipment can weigh from 60 to 70 tons, which violates the rules of transportation of goods through the territory of the Russian Federation, and complicates the process of its delivery to the country and then to the drilling rig, the best method of delivery may be the use of a carrier ship with the delivery of cargo through the Kara Sea to the port of Yamburg. After the delivery of the CT and equipment, it is necessary to obtain temporary permission to deliver it to the field located at a distance of 25-30 km from the port. Transportation issues are not influencing much on the choice of technology selection, and full-bore frac sleeves technology is most recommended for completion of well ML-1. Technology has an option for further refracturing, allows selective access to the stages, makes it possible to close and open them, and carries out workover operations.

The second recommended technology can be plug and perf. As can be seen from the analysis Table, this technology requires more capital expenses and doesn't have refracturing options, but despite this can be a good second option in case if frac sleeves transportation will have problems.

5.6 Completion construction of ML-1

This subchapter of the master's thesis completion chapter was planned and evaluated, to facilitate drilling and completion operation and eliminate additional risks during hydraulic fracturing.

Firstly, it is recommended to finish the drilling and cementing phase of ML-1 construction according to design in this master's thesis.

Secondly, completion of well according to TAML level 4, with the technological ability for converting to the TAML 5 in the future if necessary, due to problems with gas leakage through cement. The completion scheme of ML-1 according to TAML 4 and TAML 5 presented in figures 39 and 40.

The next step after completion of the well construction phase, and defining TAML level it is necessary to determine the number of HF stages and the distance between them.

Following the research conducted by Gaspromneft in the Priobskoye field, and the experience of drilling the first two horizontal wells in Yamburg, a decrease in the distance between the stages of less than 100 m will not give an effective increase in oil production, and with an increase of distance, efficiency may decrease. Therefore, it was recommended to keep distance between the stages of hydraulic fracturing 100m as it was planned in the first well and other wells in the cluster. The number of stages and lengths of horizontal sections of the wells H-1 and the ML-1 is presented in Table 23.

Table 23: Horizontal section and number of HF stages of ML-1 and H-1

Well name	wellbore	Length, (m)	Number of stages
H-1	-	1754	17
ML-1	Main	1659.5	17
	Second	1592.5	16

The completion design of production liner in the experimental well H-1 was conducted with the installation of ports with ball seats. The Full-bore frac sleeves technology selected for ML-1 and activated by CT, requires the installation of frac sleeves in the production liner too. The lower part of the liner will be equipped with fracturing ports, and the liner will be cemented only in the upper part by using stage cementing technology, as it was done in the well H-1. The design of the production liner is given in Table 24.

Table 24: Design of Production liner for Multilateral well completion.

Wellbore	Liner interval, (m)	length, (m)	Upper part Cased and cemented		Lower part Equipped with frac sleeves	
			interval, (m)	length, (m)	interval, (m)	length, (m)
Main	3842 - 6759.8	2917.8	3842 – 5100.3	1258.3	5100.3 – 6759.8	1659.5
Lateral	3842 - 6870.7	3028.7	3842 – 5278.2	1436.2	5278.2 – 6870.7	1592.5

After completion of the well construction phase, the hydraulic fracturing will be conducted in both wellbores with proposed MSHF technology. Completion scheme of the ML-1 equipped with frac sleeves presented in Figure 41.

The detailed procedure for MSHF after well construction recommended to be conducted as follows:

1. Lowering HF stinger into the main well, carrying out MSHF operations;
2. Washing out the proppant from the plug installation interval in the main well;
3. Lowering and installation of the plug on CT, conducting hydrostatic testing to check for leaks (replacement of the plug if it is necessary). During further in well operations the integrity of main well will be maintained by two barriers, plug, and hydrostatic liquid column;
4. Washing over the head of the 114 mm liner if necessary;
5. Removing HF equipment from the main well;
6. Lowering equipment for access to the lateral wellbore;
7. Lowering HF stinger into the lateral well, carrying out MSHF operations;
8. Washing out the proppant from the plug installation interval in the lateral well;
9. Lowering and installation of the plug on CT, conducting hydrostatic testing to check for leaks (replacement of the plug if it is necessary);
10. Washing over the head of the 114 mm liner in lateral well if necessary;

11. Removing HF equipment from the lateral well;
12. Removing the plug firstly from the main and lateral wells.

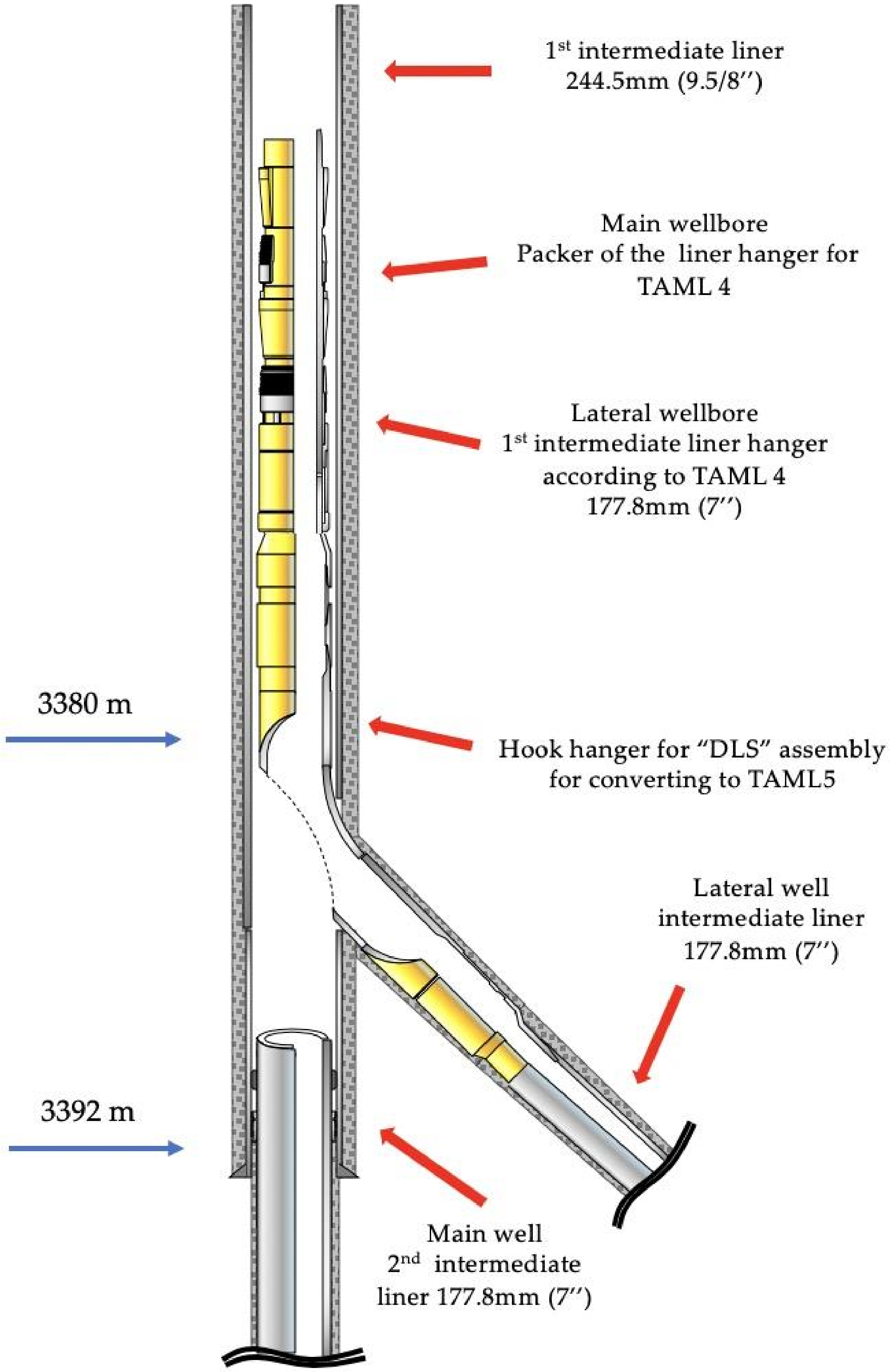

Figure 39: Completion scheme of convertible TAML 4.

The window milling for the lateral well is planned to be carried out in 244,5 (9 5/8′′) mm intermediate liner. After first well drilled and cased, the assembly with whipstock-anchor levered into the well until it reaches the top of 177.8 mm (7′′) liner of the main well and receives additional support. After the window is milled and drilling continued until the measured depth of 4092 m, the whipstock anchor removed from the well. Liner equipped with the liner hanger and the special hook-hanger with "DSM" – Dual Seal Module tool for converting TAML 4 to TAML 5 (Baker Hughes n.d.) is lowered to the lateral well. Then, the last section of lateral well with a diameter of 152.4 mm (6'') drilled and 114 mm (4 1/2'') production liner lowered and cemented by collar cementing technology. The equipment used at the junction of the ML-1 and in completion assembly presented in Tables 25 and 26.

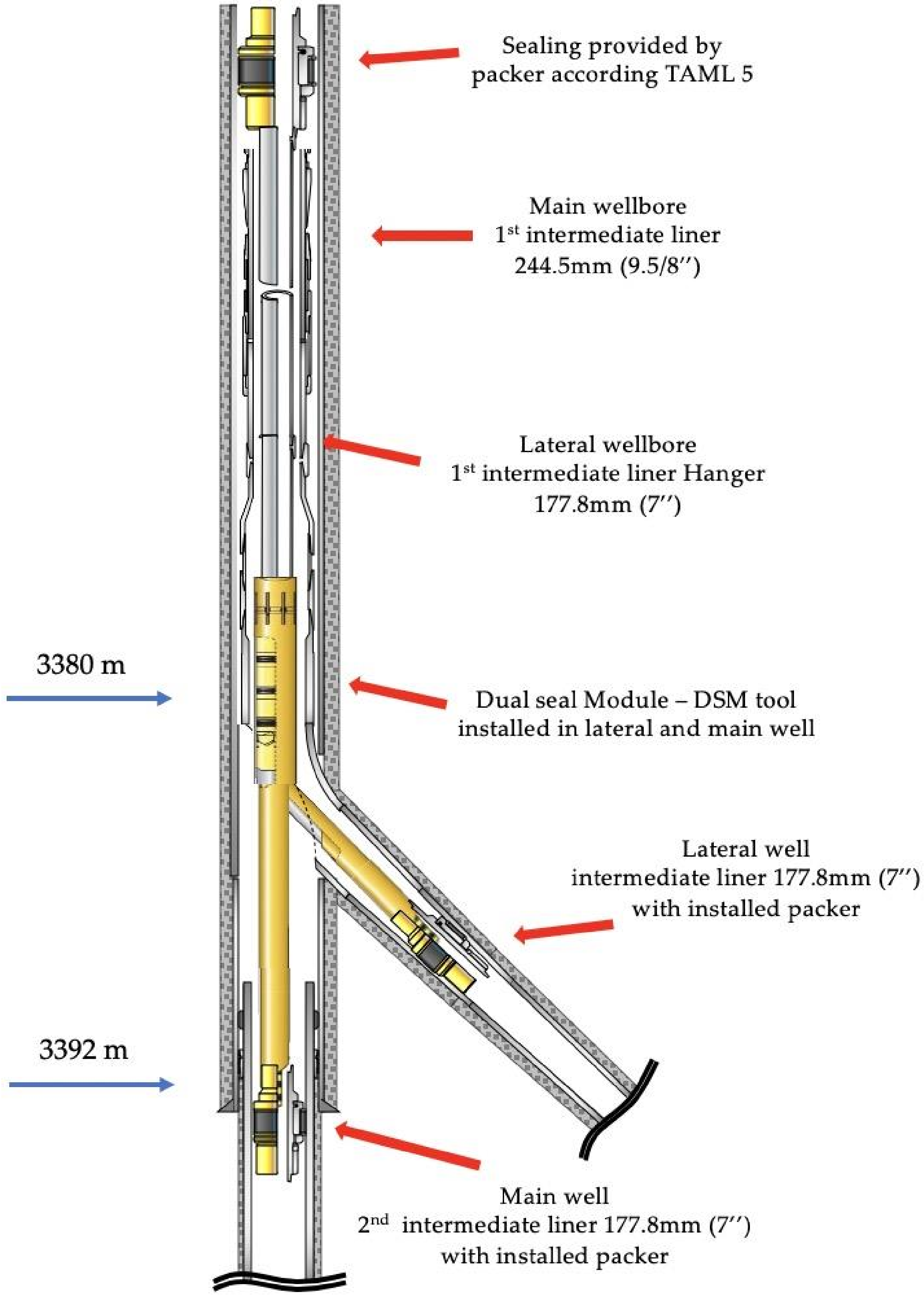

Figure 40:Completion scheme of ML-1 converted from TAML 4 to TAML 5

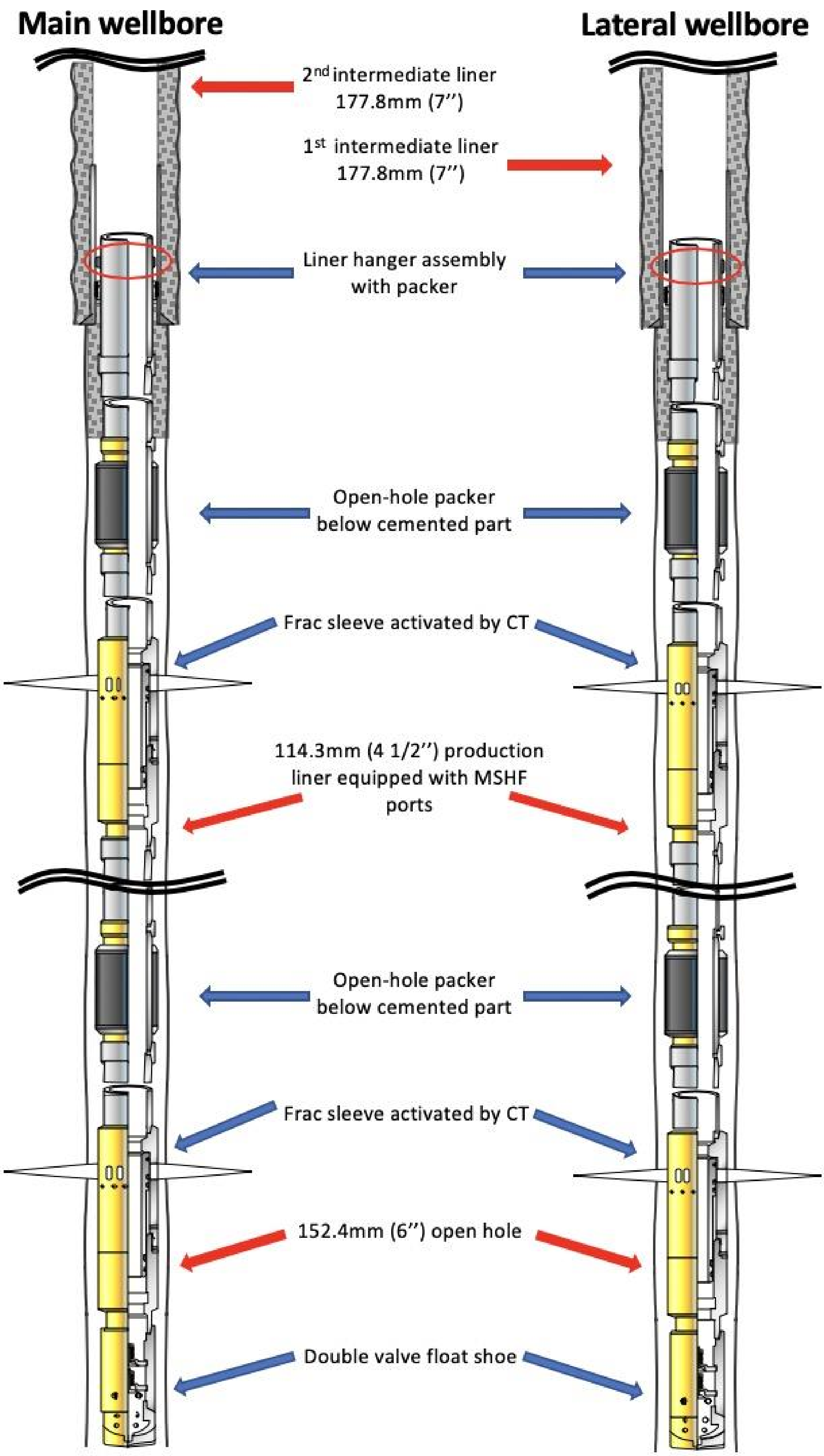

Figure 41: Completion Scheme of well ML-1, equipped with Frac sleeves

Table 25: Equipment installed at the junction of ML-1 according to the TAML 4 and 5

<table>
<tr><th>description</th><th>ID, mm</th><th>OD, mm</th><th>Open hole, mm</th><th>Setting interval MD, m</th></tr>
<tr><td colspan="5">Equipment at TAML 4</td></tr>
<tr><td>1^{st} intermediate liner</td><td>216.8</td><td>244.5</td><td>311.15</td><td>836 - 3642</td></tr>
<tr><td>Liner hanger equipped with a packer</td><td>172.5</td><td>212</td><td rowspan="2">Inside liner ID – 216.8</td><td rowspan="2">3370 -3380</td></tr>
<tr><td>Hook hanger</td><td>159</td><td>209</td></tr>
<tr><td>2^{nd} Intermediate liner of the main wellbore</td><td>159.4</td><td>195</td><td>215.9</td><td>3392 - 4092</td></tr>
<tr><td>The intermediate liner of the lateral wellbore</td><td>159.4</td><td>195</td><td>215.9</td><td>3392 - 4092</td></tr>
<tr><td colspan="5">Equipment added at TAML 5</td></tr>
<tr><td>Upper Packer at TAML5</td><td>177.8</td><td>213.9</td><td>Inside liner ID – 216.8</td><td>3370 - 3385</td></tr>
<tr><td>Packer in main well</td><td>101.6</td><td>152.4</td><td rowspan="2">Inside liner ID – 154.78</td><td>3410</td></tr>
<tr><td>Packer in lateral well</td><td>101.6</td><td>152.4</td><td>3410</td></tr>
</table>

Table 26: Equipment installed in the completion of ML-1

<table>
<tr><th colspan="2">description</th><th>ID, mm</th><th>OD, mm</th><th>Open hole, mm</th><th>Setting interval MD, m</th></tr>
<tr><td colspan="6">Main well</td></tr>
<tr><td>Production liner of the main wellbore</td><td>P - 110</td><td>99.5</td><td>114.3</td><td rowspan="4">152.4</td><td>3842 - 6759.8</td></tr>
<tr><td colspan="2">17 Open-hole packers</td><td>99</td><td>143</td><td>at every 100 m</td></tr>
<tr><td colspan="2">17 Frac sleeves</td><td>99</td><td>143</td><td>at every 100 m</td></tr>
<tr><td colspan="2">Double valve float shoe</td><td>-</td><td>127</td><td>Well toe</td></tr>
<tr><td colspan="6">Lateral well</td></tr>
<tr><td>Production liner of the lateral wellbore</td><td>P - 110</td><td>99.5</td><td>114.3</td><td rowspan="4">152.4</td><td>3842 - 6870.7</td></tr>
<tr><td colspan="2">16 Open-hole packers</td><td>99</td><td>143</td><td>at every 100 m</td></tr>
<tr><td colspan="2">16 Frac sleeves</td><td>99</td><td>143</td><td>at every 100 m</td></tr>
<tr><td colspan="2">Double valve float shoe</td><td>-</td><td>127</td><td>Well toe</td></tr>
</table>

6 Well Performance Analysis

This subchapter objective is dedicated to the prediction of the well productivity and the selection of the completion string size. PIPESIM software was chosen as a platform for the simulations. The software package consists of several multi-functional blocks, each is built for different design tasks.

- Well Performance Modeling (including the artificial lift design)
- Flow Assurance Modeling
- Network simulation and Optimization

To design multilateral well ML-1 in PIPESIM software's environment, two wellbores were designed and sensitivity analysis was done separately. The results are combined in the Microsoft Excel file.

The main task was to run the flow simulation of horizontal well being hydraulically fractured. Researching the horizontal well inflow "Babu and Odeh" model was the most suitable for the given well condition. The following three reasons made this model most suitable for simulating the well performance of well ML-1.

Firstly, the reservoir is already in production and reservoir pressure has begun to drop.

Secondly, this model allows the account of the skin factor due to partial reservoir opening (it is perforated well, not an open hole). In other words, the model enables us to enter the total perforated length.

The third reason for selecting this model is that selection of a pseudo-steady model for horizontal well with different perforated lengths requires the productivity index (PI) for each stage, which is not available and wasn't possible to model (due to lack of data provided by the Company). Instead model requires the Skin factor, which was obtained after MSHF operation on experimental well H-1.

6.1 Babu and Odeh model.

The peculiarity of the model is that it is designed pseudo stationary inflow, it takes into account the boundaries of the closed reservoir, which are not permeable, and also considers the change of pressure of the system by propagation to the well. The Babu and Odeh model consider a box-shape drainage area with the length L of a horizontal well, lying parallel to the Y-axis, taking into account coordinates of the beginning point Y1 and the ending point of length Y2. (Figure 42).

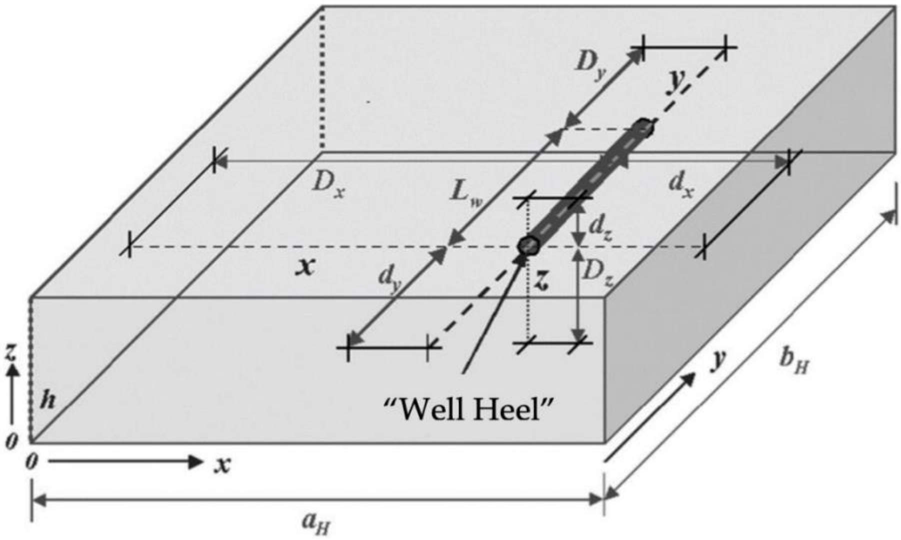

Figure 42: Babu and ' 'Odeh's box-shape model.

The productive formation has a length y and the width x across the location of the well's horizontal section, and the formation thickness – h. The position of the well in the system may vary, but it must be aligned with one of the axes. Coordinates are set by the start and end of the horizontal part of the well, in turn, the grid of coordinates itself is fixed to one of the edges of the reservoir.

The model is based on radial inflow along Y and X-axes, based on rectangular shape taking into account the geometric factor of the reservoir, the direction of inflow, and the skin factor of incomplete penetration outside the drainage zone. The general expression of pseudo stationary influx to a horizontal gas well looks like the following:

$$q_g = \frac{b \cdot \sqrt{k_y k_z} \cdot \left(p^2 - p_{wf}^2\right)}{1424 \cdot Z \cdot \mu_g \cdot T \cdot \left(\ln\left(\frac{A^{0.5}}{r_w}\right) + \ln C_h - 0.75 + S_r + S + D_{qg}\right)} \quad (3)$$

In equation:

A - cross-section area which is perpendicular to the wellbore;

C_h - the geometric factor that considers reservoir shape;

S_r – the geometrical skin factor;

S - skin factor taking into account other factors (contamination, colmatation, bottom hole damage);

D_{qg} - flow turbulence factor during filtration, not according to Darcy 's law.

The main purpose of the Babu and Odeh model calculation is to find the coefficient of the geometric shape of the deposit - C_h and the skin geometrical factor – S_r (Grassi 2015).

Model theoretically can be used and simulated to find well productivity if the values of geometric shape and skin factor are known from the previous wells. In the PIPESIM software, the following properties and input data (Table 27) were given to run simulations.

Table 27: Input (reservoir, well, and fluid) properties used in the simulation.

№	input	values	
		Main well	Lateral well
1	reservoir pressure, bar	650	
2	reservoir temperature, C	116	
3	Reservoir length in the X dimension, m	6960	
4	Reservoir length in the Y dimension, m	3825	
5	reservoir thickness, m	98	
6	permeability in the X direction, mD	100	
7	permeability in the Y direction, mD	100	
8	permeability anisotropy, -	1	
9	heel location – X, m	1348	2343
10	heel location – Y, m	6554	6665
11	heel location – Z, m	49	
12	horizontal section length, m	1659.5	1592.5
13	well radius, mm	74.5	
14	oil formation volume factor (OFVF), -	2.322	
15	fluid viscosity, cP	23	

6.1 Sensitivity analysis for ML-1

The Sensitivity analysis is a mathematical approach that determines how the output variables are affected based on changes in the input variables. The sensitivity model is also referred to as "what-if" or "simulation analysis". It is a technique to predict the outcome of a decision given in a certain range of variables. Some important reservoir parameters cannot be 100% refined, and a sensitivity analysis is being performed to determine their effect on the final well productivity. The reservoir parameters as permeability and its anisotropy were given as interval values when drilling well H-1.

6.1.1 Rock permeability sensitivity analysis

Natural formation fractures and fractures artificially created by HF are the main flow path for a fluid movement from the high-pressure area of the reservoir to the wellbore with the low-pressure area. Due to the complex structure of Achimov' 's formation, the permeability value was given as a range. The given range from documentation of well H-1 was used. Designed multilateral well with MSHF (100m between stages) was evaluated through 20 simulations with different formation permeabilities in the function of reservoir pressure. The simulation results are given in Table 28 and Figure 43 at different formation pressures.

Table 28: Performance of simulated multilateral with different permeabilities at different reservoir pressures.

№	Permeability, mD	Flow rate, m^3/d			Reservoir Pressure, bar
		Main wellbore	Lateral wellbore	ML-1, (total)	
1	0.1	0.5270343	0.4959307	1.022965	450
2	1	8.642747	8.42933	17.07208	
3	10	89.80322	88.57115	178.3744	
4	100	654.5231	640.082	1294.605	
5	0.1	0.6555062	0.6235702	1.279076	500
6	1	10.01405	9.839804	19.85385	
7	10	102.0773	100.7782	202.8555	
8	100	735.4908	719.6716	1455.162	
9	0.1	0.7841638	0.751286	1.53545	550
10	1	11.3025	11.15059	22.45309	
11	10	114.3601	112.9898	227.3499	
12	100	815.3919	798.1712	1613.563	
13	0.1	0.9129403	0.8798254	1.792766	600
14	1	12.54844	12.4011	24.94954	
15	10	126.6389	125.1991	251.838	
16	100	893.9481	875.3505	1769.299	
17	0.1	1.042001	1.008088	2.050089	650
18	1	13.79491	13.64215	27.43706	
19	10	138.9348	137.4306	276.3654	
20	100	971.3614	951.38	1922.741	

It can be seen that the permeability of the formation strongly affects well productivity. The higher the permeability of natural cracks, the lower the fluid flow resistance, and consequently, the higher the fluid production. When formation permeability is below 0.01 mD, the accumulated liquid production is relatively low and cannot meet the minimum economic requirement. Thus, analysis confirms that with HF, many parts of the reservoir would not have a significant contribution to the total production, and full well potential wouldn't be reached without HF.

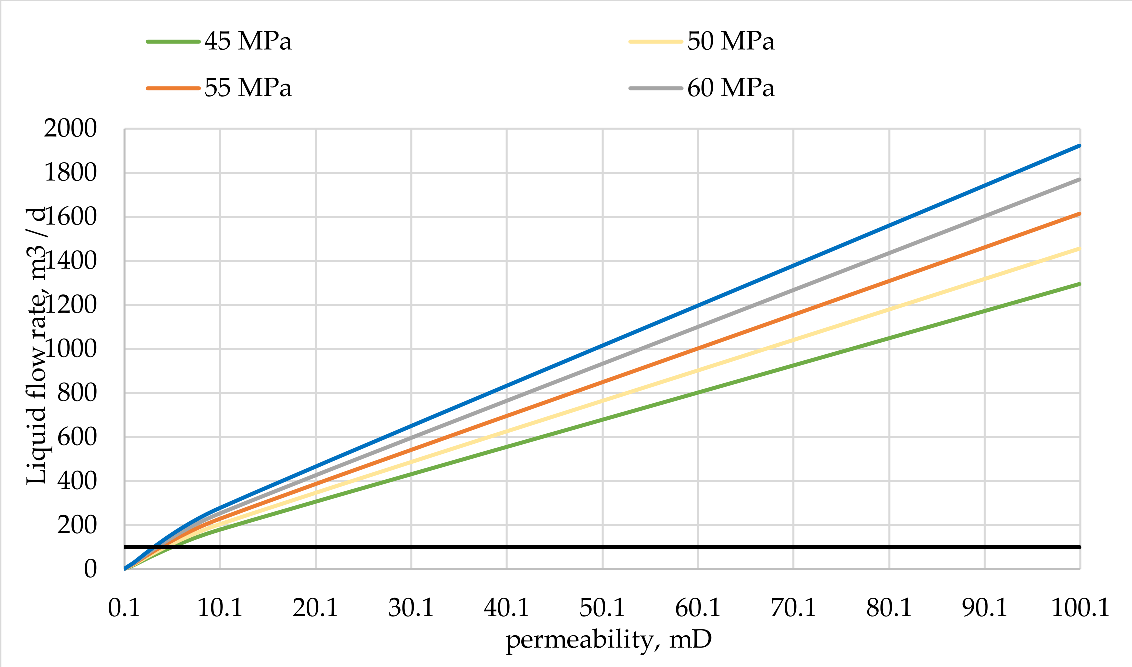

Figure 43: Influence of permeability on well performance at different reservoir pressures

6.1.2 Horizontal section length sensitivity analysis

In this part of the thesis, 16 simulations were performed with different lengths of the horizontal section of both wells. For each variant, the interval between the HF stages is 100 m, permeability is 100 mD, 6 sleeve holes located at each stage (in the fracking sleeve) of the HF. The results in the function of reservoir pressure are shown in Table 29 and Figure 44.

Table 29: Performance of multilateral well with MSHF at different lengths of HS

№	length of horizontal section, m	Flow rate, m3/d			Reservoir Pressure, bar
		main wellbore	lateral wellbore	ML-1 (total)	
1	400	335.3303	345.7297	681.06	450
2	800	502.6766	507.3431	1010.02	
3	1200	595.0262	592.8865	1187.913	
4	1600	648.7619	640.7583	1289.52	
5	400	379.4959	391.3193	770.8152	500
6	800	566.6211	572.0525	1138.674	
7	1200	669.4736	667.3048	1336.778	
8	1600	729.123	720.419	1449.542	
9	400	423.2769	436.6118	859.8887	550
10	800	630.0344	636.1868	1266.221	
11	1200	743.1217	740.7789	1483.901	
12	1600	808.4085	798.9908	1607.399	

№	length of horizontal section, m	Flow rate, m3/d			№
		main wellbore	lateral wellbore	ML-1 (total)	
13	400	466.8608	481.6313	948.4921	600
14	800	692.742	699.5678	1392.31	
15	1200	815.6273	813.2258	1628.853	
16	1600	886.3441	876.2361	1762.58	
17	400	510.0948	526.2935	1036.388	650
18	800	754.8056	762.2699	1517.076	
19	1200	887.2913	884.6686	1771.96	
20	1600	963.2395	952.3314	1915.571	

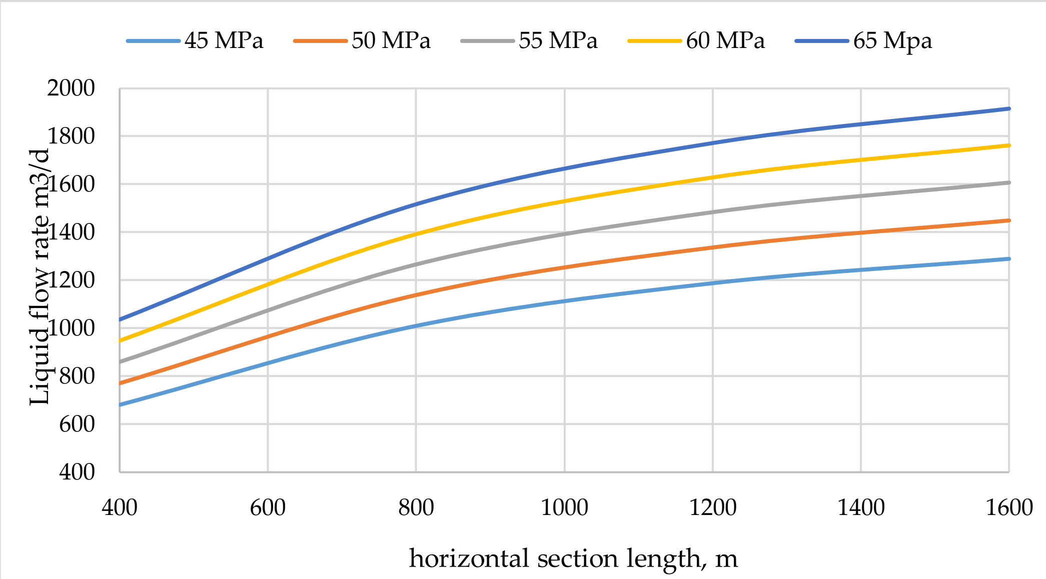

Figure 44: Well performance with different HS lengths at various formation pressures

The results of the simulation show that with the elongation of the horizontal section, the productivity of the wells increases with logarithmic dependence, both before and after the HF. This is because the drainage area increases with the length of the horizontal section, and accordingly, the well productivity is improved. Apart from physical constraints, the length of the horizontal section is also limited for economic reasons and technical reasons. From the technical point of view, longer the well, more complicated to carry out in well and workover operations. Besides, according to the telescopic shape of wells design, longer well will be, the smaller will be production liner/casing. This limits the productivity of the well at the beginning of production and decreases the economic expediency of the project. From an economic point of view, the length of the horizontal section significantly affects the cost of drilling the well and the cost of the produced oil. Although with the increase of the horizontal section length, the productivity of the well increases linearly, however the fluid production per unit length of the well's horizontal section decreases. Thus, the horizontal section cannot be indefinitely extended, and there is an optimal value for the length of the horizontal section. The presented analysis shows that the optimal length of the horizontal section under the conditions of the Achimov deposits can be in the range of 1400-1500 m. With the further increase in the length of the horizontal section, the increase in productivity reduces, which is not economically feasible.

6.1.3 Anisotropy sensitivity analysis.

In this paragraph, the results of the permeability anisotropy of the well ML-1 will be presented. Permeability is one of the essential parameters of the formation. The measurement of the vertical permeability may give different values from the perpendicular values at the same point in the reservoir. The change of any measurements' value in different directions called anisotropy. Anisotropy can significantly influence the well performance and improve the coverage ratio. Various values of permeability are defining the anisotropy in different directions. (Cosan Ayan n.d.). The anisotropy of permeability is considered as one of the important input parameters in reservoir engineering and in creating the 3D reservoir models for fluid flow simulations. Therefore, the anisotropy sensitivity analysis was performed to check the influence on the production rate.

Table 30: Performance of multilateral well at different permeability's anisotropy in the function of reservoir pressure.

№	Permeability anisotropy, K_v/K_h	Flow rate, m3/d			Reservoir Pressure, bar
		main wellbore	Lateral wellbore	ML-1	
1	0.01	424.0619	410.5196	834.5815	450
2	0.1	584.8486	570.1967	1155.045	
3	0.4	635.0883	620.5373	1255.626	
4	1	654.5231	640.082	1294.605	
5	0.01	478.9421	463.9934	942.9355	500
6	0.1	658.2374	642.1614	1300.399	
7	0.4	713.9924	698.0464	1412.039	
8	1	735.4908	719.6716	1455.162	
9	0.01	533.3479	516.9847	1050.333	550
10	0.1	730.655	713.3122	1443.967	
11	0.4	791.8241	774.4702	1566.294	
12	1	815.3919	798.1712	1613.563	
13	0.01	587.2735	569.5433	1156.817	600
14	0.1	802.2191	783.3186	1585.538	
15	0.4	868.4534	849.7223	1718.176	
16	1	893.9481	875.3505	1769.299	
17	0.01	640.7097	621.6301	1262.34	650
18	0.1	872.841	852.5109	1725.352	
19	0.4	944.0129	923.8818	1867.895	
20	1	971.3614	951.38	1922.741	

As seen from Figure 45, the increase of anisotropy can significantly increase the performance of well producing from low permeable formations. The more the values differ from each other, the higher the anisotropy will be. The maximum value of the anisotropy is 1. It is reached when the values of permeabilities in both directions are the same. However, the influence rate of anisotropy drops with an increase in the well performance. It is advised to consider anisotropy of permeability during drilling future wells, to achieve the greater value of it, which will sufficiently influence on well productivity.

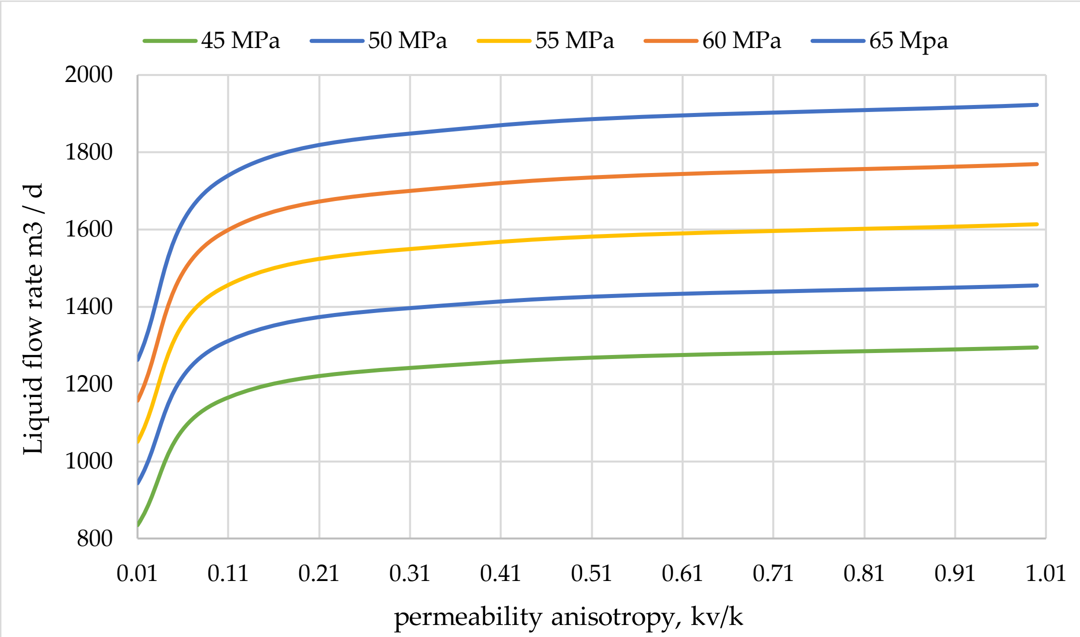

Figure 45: Well performance with different anisotropy at various formation pressures.

7 Conclusion

Every year the reserves of the field with good filtration properties decrease, and companies move towards the creation of technologies allowing them to develop deposits with poor filtration properties. Gazprom Neft, with the Yamburg field development project, is an existing example of this. In recent years geological and geophysical studies have made it possible to study Achimov deposits and the field as a whole in detail. The research and then application of MSHF technology at the Priobskoye field with relatively similar formation characteristics, and drilling of the first experimental well of H-1 will make it possible to ensure the efficiency of MSHF, in these formation conditions. The design of the wells with three liners showed its economic benefit. The project for the construction of an ML-1 well, and the choice of its completion technology, can be a good continuation for the development of the project. Drilling a multilateral well instead of two horizontal wells will significantly reduce the cost and time to build a well. Selection of the well's completion level according to the TAML classification, MSHF technologies, and comparison of these technologies, which were considered and answered in this master 's thesis, can help to the Yamburg field development plan and be taken into account in the development of other fields with low-permeability formation properties of Siberia. The technology of intelligent wells completion, established abroad, may also help the intelligent development of the field. The completion design of the liner with swellable packers and ICD between each fracturing stage maybe a good solution. However, the application of this technology in the fields of Siberia requires further study, and economic estimations to understand how much benefit will be gained in the creation of a smart well.

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