EXPERIENCE IN NORTH AMERICA TIGHT OIL RESERVES DEVELOPMENT. HORIZONTAL WELLS AND MULTISTAGE HYDRAULIC FRACTURING

R.R. Ibatullin
TAL Oil Ltd., Calgary, Canada
E-mail: ravil.r.ibatullin@gmail.com

The accelerated development of horizontal drilling technology in combination with the multistage hydraulic fracturing of the reservoir has expanded the geological conditions for commercial oil production from tight reservoirs in North America. Geological and physical characteristics of tight reservoirs in North America are presented, as well as a comparison of the geological and physical properties of the reservoirs of the Western Canadian Sedimentary Basin and the Volga-Ural oil and gas province, in particular, in the territory of Tatarstan. The similarity of these basins is shown in terms of formation and deposition.

New drilling technologies for horizontal wells (HW) and multistage hydraulic fracturing are considered. The drilling in tight reservoirs is carried out exclusively on hydrocarbon-based muds The multistage fracturing technology with the use of sliding sleeves, and also slick water – a low-viscous carrier for proppant is the most effective solution for conditions similar to tight reservoirs in the Devonian formation of Tatarstan. Tax incentives which are actively used for the development of HW and multistage fracturing technologies in Canada are described.

Key words: North America, tight oil, sandstone, carbonate, horizontal wells, multistage fracturing

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There is the rapid growth of the new technics and technologies in the development of unconventional hydrocarbon reserves in the last decade. Among them are drilling of horizontal and multilateral wells, as well as technology, equipment, and reagents for multistage hydraulic fracturing (MSF) for tight oil and shale oil. This has opened new opportunities for effective industrial development of the vast unconventional resources in shale and tight reservoirs.

These technologies are most effectively used in North America, where hydrocarbons in tight and shale reservoirs are extended over a large territory (Fig.1).

The most rapidly developing area in the United States in the last three post-crisis year is the Permian basin. This basin is located in the country's south, where is the third US active drilling rigs for oil (over 300 units) and about half of the total US rig count. Hydrocarbon deposits of the Permian basin are located at depths of 2500-3000 m in the shales within area's porosity value above 5%.

In Canada, similar resources are located in the Western Canadian Sedimentary Basin (WCSB), a brief description of which is presented in table 1.

Upper Devonian sediments in WCSB were formed mainly under conditions of shallow coastal sedimentary environments, including reef sediments of Leduc. Their location is shown (Stacy C. Atchley, Lawrence W. West, Jeff R. Sluggett, 2006) in the center, and also in the right of part B (Fig. 2). In the 30-s of the last century, the discovery of these reserves marked the beginning of the oil boom in Canada, similarly to Sakmara-artinsky reef sediments of the Ishimbay oil field which was opened in Bashkortostan, Russia at the same time. The counterpart of these carbonate reservoirs in Tatarstan in reservoir characteristics are Dankovo-Lebedyansky, the Zavolgsky and Yeletsky deposits of the South-Tatar arch of the South-East of Tatarstan (Table 2), and for the Cardium sandstone it is Kynovsky formation of the Devonian age (Table 3).

Development of oil reserves in tight reservoirs and shales in the United States and in Western Canada in the last 5-7 years is dramatically intensified on the basis of new highly efficient technologies for horizontal wells and MSF.

These technologies have created a new investment policy with large upfront capital costs and an accelerated return due to the large initial production rate. The difference of the tight reservoir development in comparison with conventional reservoirs arises due to the emergence of significant short-term fracturing impact in the case of the tight reservoir. It should be noted, that comparable changes in pressure drop will be observed: for a tight reservoir at distances up to ten meters from the fracture, but for conventional reservoirs in hundreds of meters. This explains the presence of two legs on the decline curves on a logarithmic scale (Fig. 3). The initial hyperbolic part of the curve describes a reaction of the near-fracture zone, and further is the effect of the boundary energy (a remote area). The decline curves are applied for the recoverable oil reserves assessment widely, so the using only an initial dependence in the

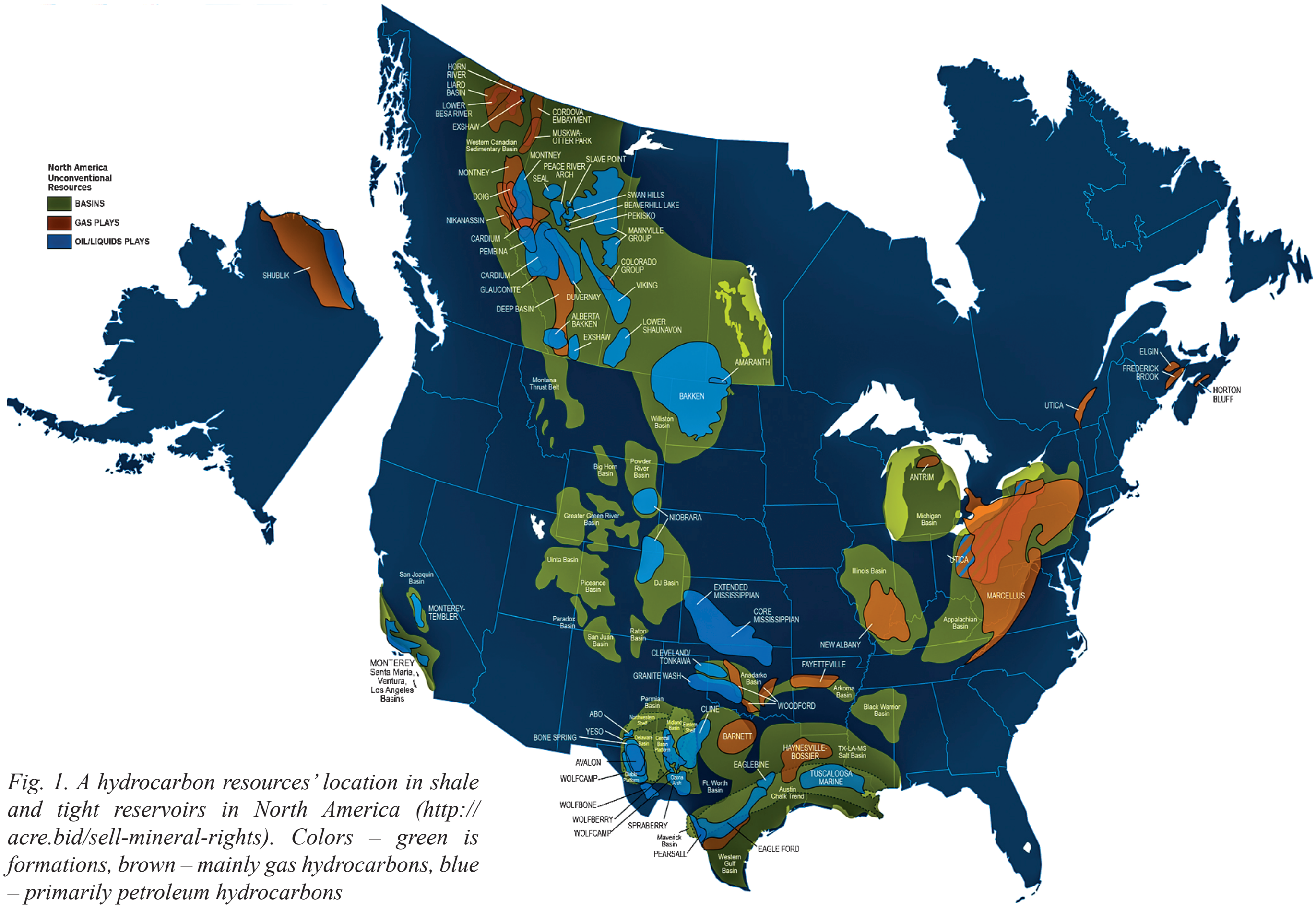

Fig. 1. A hydrocarbon resources' location in shale and tight reservoirs in North America (http://acre.bid/sell-mineral-rights). Colors – green is formations, brown – mainly gas hydrocarbons, blue – primarily petroleum hydrocarbons

Formation (Canadian Province)	Reservoir type/Age	Typical depth, m
Bakken/Exshaw (Saskatchewan, Manitoba)	Sandstone/Devon	900-2500
Cardium Formation (Alberta)	Sandstone / upper Cretaceous	1200-1600
Viking formation (Alberta, Saskatchewan)	Sandstone /low Cretaceous	600-900
Lower Shaunavon (Alberta)	Limestone mixed with shale and minor sandstone /middle Jurassic	1300-1600
Montney/Doig (Alberta, British Columbia)	Sandstone / low and middle Triassic	800-2200
Duvernay/Muskwa (Alberta)	Carbonate /middle Devon	2000+
Beaverhill Lake (Alberta)	Carbonate / middle Devon	2000-2900
Slave Point (Alberta)	Carbonate / upper Devon	1200-1500

Table 1. Characteristics of the tight reservoirs and shale plays in the Western Canadian Sedimentary Basin

continuation of a trend (the graph shows a solid line) will lead to overestimating of reserves.

In the recent low hydrocarbon price environment, a drastic cost reduction of services in North America was achieved while increasing the technological efficiency of HW drilling and hydraulic fracturing.

There is the presence, often significant, of clay components in tight reservoirs and shales. To protect swallowing and the collapse of the borehole rocks the hydrocarbon based drilling muds ("invert") are used only. This kind mud significantly reduces complications during drilling and the subsequent installation of the sophisticated completion tool for MSF.

The important reserve of the cost reduction is also cheaper equipment and maximizing the runtime of the expensive and limited of hydraulic fracturing fleet. One of the latest innovation in this field was the NCS company's (Canada, USA) fracturing technology named as the "sliding" sleeves. This technology allows conducting high-speed MSF (e.g. for 9-11 hours at 1500 m horizontal leg 30 fractures with the injection of up to 50 tons of proppant in each) by using a coiled tubing and the straddle packer system.

High formation pressure can limit coil tubing using because of its flexibility. In this case, the successive opening of fracturing stage valves by balls is mostly used technology. To mill balls and valve seats are necessary at the end of such process. To exclude these steps materials are developed which dissolved in acids or disintegrated in the salt solutions at high temperatures for acid-free systems. An example of the latter is packed compound of fiberglass, cyanate ether of resin, and a crosslinker.

Another widespread shift of the modern fracture technology for tight reservoirs and shales is "slick" water as fracturing fluid. The viscosity of such fracturing

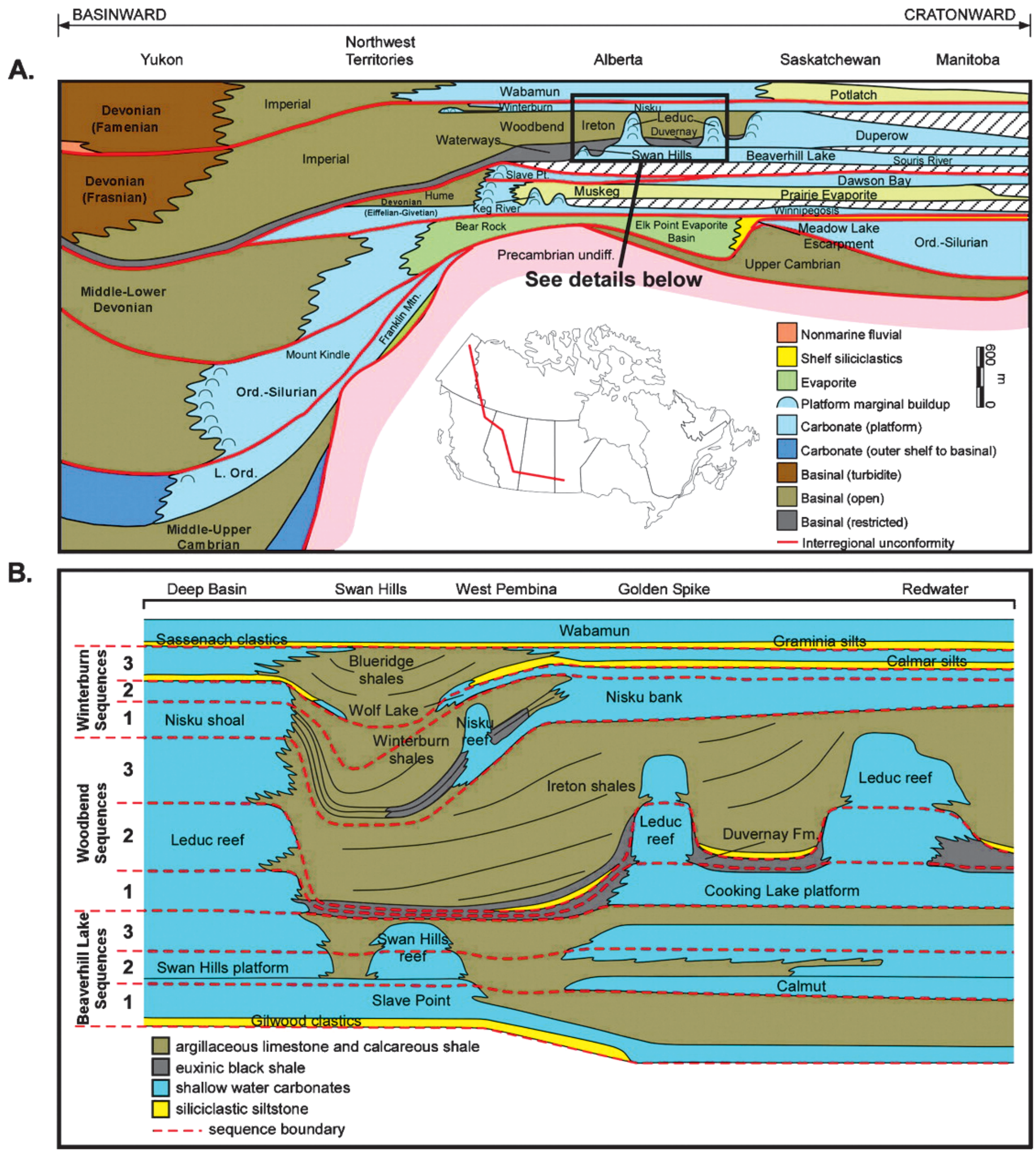

Fig. 2. Crossection of the Western Canadian Sedimentary Basin in the territory of Alberta (Stacy C. Atchley, William Lawrence West, Jeff R. Sluggett, 2006)

Parameters	Red Earth и Sawn Lake	Devonian formations in Tatarstan		
Age, formation	Upper, middle Devon, Beaverhill Lake	Zavolgsky	Dankovo-Lebedyansky	Yeletsky
Depth, m	1380	1100	1300	1500
Total thickness, m	<30	< 93	< 200	< 138
Net thickness, m	12-18			
Porosity range, %	4-15	0,5-18,7	0,3-10,9	2,2- 15,5
Average porosity, %	6			
Permeabiliy, md	0,1-10	0,01-97,3	0,01-96,6	0,09-22,5
Water saturation, %	35			
Formation temperature, °C	34	25-29	25-35	30-31
Initial pressure, MPa	9-14	10-15	9,4-13,6	14,2-15,2
Oil density, kg/m^3	840	859-942		

Table 2. Comparison of the tight carbonate reservoirs of the South-East of the Republic of Tatarstan and WCSB's Red Earth and Swan lake fields parameters

Oil field	Pembina	Romashkinskoye
Age, formation	Cretaceous, Cardium	Devon, Kynovsky
Typical depth, m	1200-1600	1700-1800
Total thickness, m	<20	<20
Net thickness, m	3-6	3-8
Porosity range, %	5-15	< 15
Permeability, md	0,1-5	< 200
Formation temperature, °C	34	
Initial pressure, MPa	12-17	17-19
Oil density, kg/m^3	830	

Table 3. Comparison of the Kynovsky Devonian formation of the Romashkinskoye oil field and Cardium formation of the Pembina field characteristics

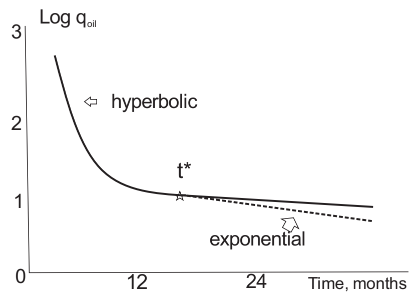

Fig. 3. The time dependence of the oil production rate for HW with MSF in semi-logarithmic coordinates (the continuous black line shows hyperbolic dependence, the dashed one is an exponential line), t is a time of transition from the predominantly fracture inflow to the predominant inflow due to the boundary energy*

fluid is lowered to 5 MPa*s while saving the retaining properties to keep the proppant (sand) in the suspended condition by using a low concentration polymer solution. On this basis, you ensure that the sand will penetrate easy into the fracture space for tens of meters by a standard fracturing fluid injection procedure.

The evolution of MSF technology shows that the efficiency for tight, predominantly hydrophobic reservoirs, grew chronologically in the following sequence of used fluids: oil-based gels, water-based gels, and, finally, “slick” water. Wide field experience approves higher efficiency of “slick” water fracturing technology for tight reservoirs and shales.

The volatility of oil prices leads to implement more “aggressive” technology of hydraulic fracturing, which consists of a larger number of fractures per horizontal length, the volume of proppant injected, and an injection rate of fracturing fluid. In addition, there is compacted wells’ spacing in modern projects.

The pilot fracturing optimization by the density of fractures and proppant mass per HW length (Jaripatke, Samandarli, McDonald & Richmond, 2014), was held by Pioneer Natural Resources (PNR) in the Eagle Ford oil field in Texas (Table 4, fig. 4). The true vertical depth is about 3500 m, porosity near 5-6%, and rock material is carbonate with permeability less 0,01 md. MSF was performed according to the “Plug and Perf” method by applying clusters of fractures. A cluster is a group of perforations/fractures formed by one perforating tool in one run.

The results of the pilot fracturing optimization in the object B has been assessed by four different methods (Jaripatke, Samandarli, McDonald & Richmond, 2014):

1. Normalized production rates;
2. Decline curves;
3. Rate Transient Analysis -RTA;
4. Reservoir modeling.

Table 5 summarizes all the pilot results assessment obtained by the mentioned authors.

Pioneer has continued MSF optimization in 2017 in more “aggressive” manner. The distance between the clusters is reduced from 15.2 m to 9.1 m, and the proppant specific consumption is increased from 810,8 kg/m to 1351,3 kg/m.

PNR has led the modification of the MSF and field development plans in the Permian Basin also. Generally, the evolution of the MSF parameters over the years is presented in table 6 (Pioneer Natural Resources, 2017). The depth of the lower Permian deposits (Wolfcamp

Pilot objects (number of wells)	Parameters		
	Proppant mass per HW length, kg/m	Distance between clusters, m	Combination (2)+(3)
1	2	3	4
A	(4 wells)	(4 wells)	(4 wells)
B	(3 wells)	(3 wells)	(3 wells)
Values for regular/pilot	540,5 / 810,8	21,3 / 15,2	

Table 4. Pilot MSF parameters in the Eagle Ford field to assess the effectiveness of multistage characteristics by using increasing specific proppant mass per HW length and the density of fracture clusters (regular/pilot)

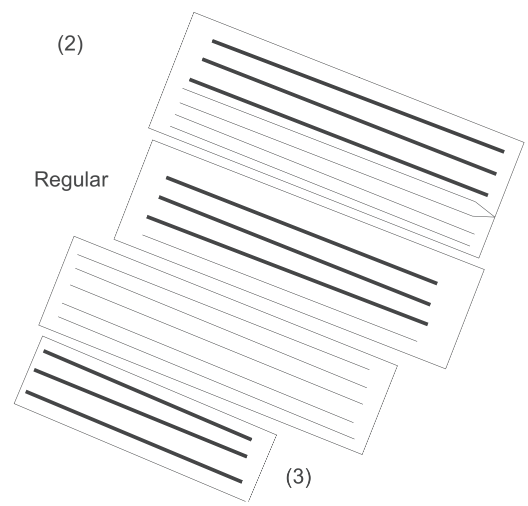

Fig. 4. PNR pilot groups’ location on the object B of the Eagle Ford field. Assigned increased thickness of the pilot wells’ projection from the table 4: (2) – increased the proppant specific consumption (810,8 kg/m); regular – the specific proppant consumption 540,5 kg/m, the distance between clusters -21,3 m; (3) increased specific consumption proppant (810,8 kg/m) and decreased distance between clusters (15.2 m)

MSF optimization method	Assessment methods			
	Normalized production rates	Decline curves	Rate Transient Analysis	Reservoir modelling
Increased proppant specific consumption	For 4 months 7% For 12 months 11%	21%	13%	11%
Increased proppant specific consumption and decreased distance between clusters	For 4 months 37%	42%	71%	49%

Table 5. The results of the pilot MSF optimization. Increase in cumulative production compared to the baseline method, % (Jaripatke, Samandarli, McDonald & Richmond, 2014)

MSF parameters	Years		
	2013-2014	2015-2016	2016-2017
Proppant specific consumption, кг/м	676	946	1149
Specific injection rate of fracturing fluid, m^3/m	15,64	18,76	26,05
Distance between clasters of fractures, m	18,28	9,14	4,57
Distance between fracturing stages, m	73,15	45,72	30,48

Table 6. Evolution of the MSF parameters which realized by the company Pioneer Natural Resources in the Permian Basin in 2013-2017

and Spraberry formations) is 1500-3000 m, MSF was performed by the method Plug and Perf.

In order to realize such advanced technology more powerful fracturing equipment with high run time is applied, thereby reducing time to reach production. Today's horizontal well pad under multistage fracturing is similar to a large plant with a maximum concentration of technologies and equipment with minimal time for the moving and installation/dismantling.

The waterflooding is effectively used at some tight reservoir conditions. Comparison with the classical waterflooding of conventional reservoirs demonstrates that tight reservoir pressure maintenance effectively assists oil displacement from the hydrophilic matrix, but does not allow to conduct direct oil displacement because of low permeability. Tight carbonate reservoirs and shales are frequently overpressed that stimulates a high initial oil rate just after fracturing, and in such case, they are mostly hydrophobic thus rarely waterflooded.

An important factor in the sustainability of the oil industry in Canada is tax incentives for new HW and fracturing technologies, which is based on a single well oil production recording system, with the lowered royalty rates to provide a certain coverage of costs for drilling the HW and fracturing. The value of the low royalty rate production depends on the depth of the reservoir, the length of the HW and the volume of proppant injected.

A reduced royalty rate of 5% is introduced in Alberta from 1st January, 2017 for oil produced by new HW with MSF for the certain value of the total revenue calculated based on the following equations (Alberta Energy Regulator, 2016):

For instance, this value for wells with true vertical depth shallower than or equal to 2 km is a following:

$$C^* (C\$) = ACCI^*((1170^*(TVD_{MAX} - 249)) + (Y^*800^*TLL) + (0.6*TVD_{AVG}*TPP)). \quad (1)$$

Where:

$C^*(\$)$ – The Drilling and Completion Cost Allowance (C$);

ACCI – Alberta Capital Cost Index, and custom government of Alberta on an annual basis to maintain the competitiveness of investments and growth in drilling and fracturing efficiencies, which adopted by 2017 equal to 1.0. For future years, an estimation is expected the rate of 3% per year;

TVD_{MAX} – The deepest True Vertical Depth (m);

TVD_{AVG} – The average True Vertical Depth (m) for all legs (non-reported legs included as zero);

TLL – Total Lateral Length (m);

TPP – Total Equivalent Proppant Placed (tonnes);

TMD – Total Measured Depth (m) (i.e. Combined total length for all legs);

Y – a cost adjustment for multileg wells to better reflect actual costs – Y = 1 if the ratio of $TMD/TVD_{AVG} < 10$, otherwise Y equals the greater of 0.24 and $[1.39 – 0.04*(TMD/TVD_{AVG})]$.

To estimate the value of the Alberta province support will take the modern data for HW and MSF for the Pembina field. Let's calculate according to the equation (1) for a single-leg horizontal well with 35 hydraulic fracturing stages and 20 tons of proppant in each, with the following parameters:

TVD_{MAX} – 1600 m;

TVD_{AVG} – 1600 m;

TLL – 1600 m;

TPP – 700 tons;

TMD – 3400 m.

The resulted marginal revenue covered by 5% royalty is 3.53 million C$. Assume the cost HW with MSF for mentioned conditions above was about 2 million C$. In order to obtain the specified revenue at an oil price of 55 C$/bbl (43,8 USD/bbl in according to the exchange rate on 15.07.2017) will need to produce approximately

64,000 barrels of oil. With average production rate up 100 bbl/day, it takes near 2 years. When operating costs are 20 C$/bbl net revenues is 2.2 million C$. So, the incentive royalty rate allows the company to generate revenues to cap full cost of the new well in relatively short time.

After reaching the marginal revenue for incentive taxation, the regular rate comes into effect where the royalty rate depends on the production rate and world market oil prices (the marginal rate for high flow rates and highest prices – up to 40%).

A similar approach is implemented in Alberta regarding enhanced oil recovery projects, as well as projects with high geological risks, from 1st January 2017.

Conclusion

1. The high efficiency of modern technologies for the development of unconventional resources in North America along with the tax incentives allows providing sustainable development of the previously marginal resources even in conditions of low hydrocarbon price environment.

2. The new MSF technologies are aimed to minimize costs and achieve maximum production rate in a very short time. This is provided by a higher density of fractures, the increase the specific volume of the injected proppant per fracture, and the high flow rate of the fracturing fluid.

3. The tax regulation for hydrocarbon production in Alberta allows achieving payback for HW and MSF projects in low royalty rate borders. The same approach is adopted for projects of enhanced oil recovery, as well as the development of reserves in uncertain geological conditions. This promotes to reduce risks and facilitate the loans for business development.

4. The Volga-Ural oil and gas basin's substantial resources of light hydrocarbons in tight reservoirs can be an important engine for oil and gas industry in the nearest future.

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About the Author

Ravil R. Ibatullin – DSc (Engineering), Professor, Director, TAL Oil Ltd.

800, 350-7th Avenue SW Calgary AB Canada T2P 3N9

Tel: +1-(403)-705-1935, e-mail: ravil.r.ibatullin@gmail.ru

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