Exploitation of Light Tight Oil Plays

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The article gives an overview of light oil production from tight rocks from the aspect of petroleum reservoir engineering. The topics are: definition and properties, practical results, research to improve the recovery efficiency, significance of tight oil production and economics.

At present, the used natural depletion of these resources gives a very modest recovery factor. The improved methods are in laboratory or pilot scale only. The article outlines problems, which moderate the recovery efficiency, also including possible recovery processes. The realization of effective recovery of this type of accumulations represents a significant task for researchers and technical specialists. Most likely these efforts will produce good results in the near future in supplying a part of the primary energy consumption.

Key words: tight reservoirs, estimation of unconventional oil, production, economics

Introduction

The exploitation of petroleum reservoirs or accumulations is discussed by e.g. Pápay J. (2003 and 2013).[15,16] The two books integrate almost every type of recovery methods from the aspect of reservoir engineering. During writing and editing of the second book (time frame: 2010-2013 years) mainly tight light oil production has increased tremendously in the USA and partly in Canada. Discussion of this type of exploitation technology is missing from the book of Pápay J. (2013).[16] This is why this recovery method is discussed here.

Figure 1. presents the relation between the original mobility (not stimulated) and costs qualitatively for different hydrocarbons. Figure 2. demonstrates the classification of unconventional oil recovery methods. The exploitation

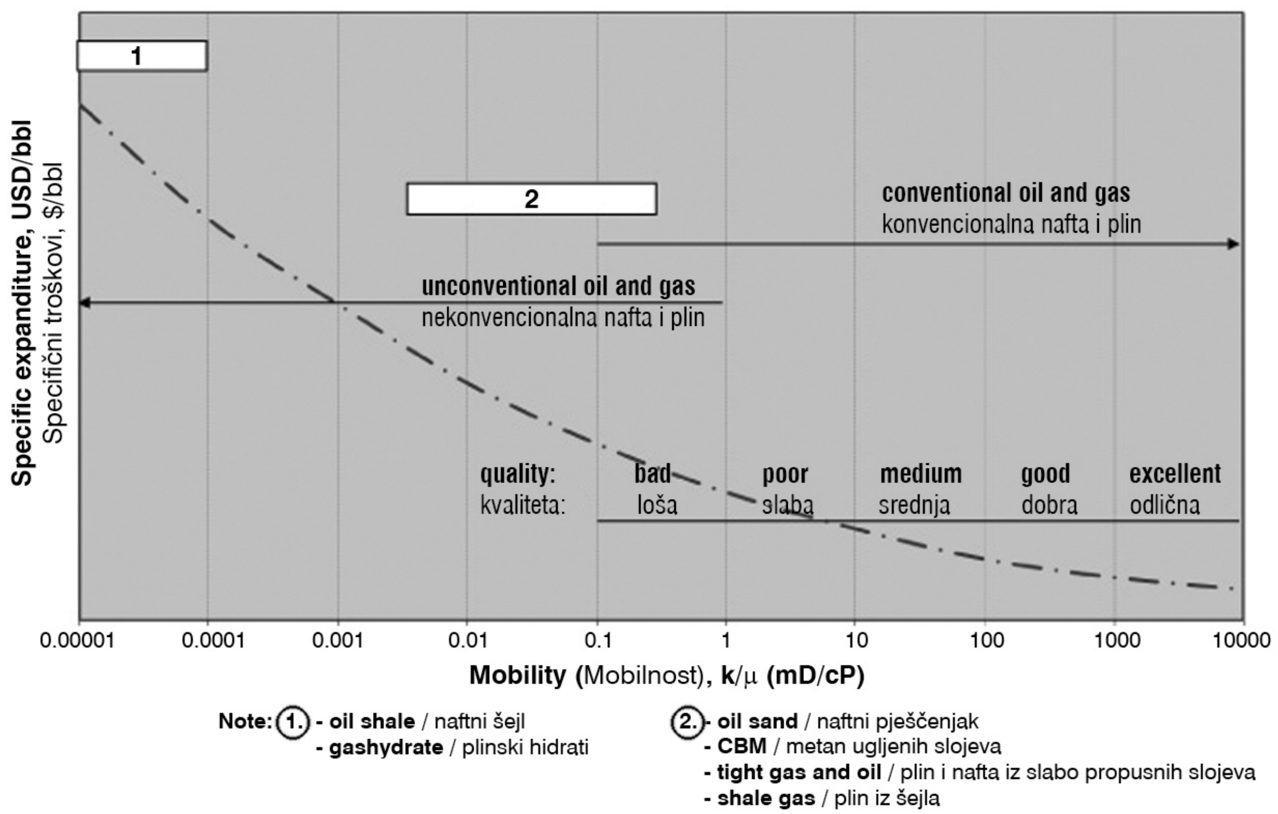

Fig. 1. Relation of mobility and cost
Sl. 1. Odnos mobilnosti i cijene

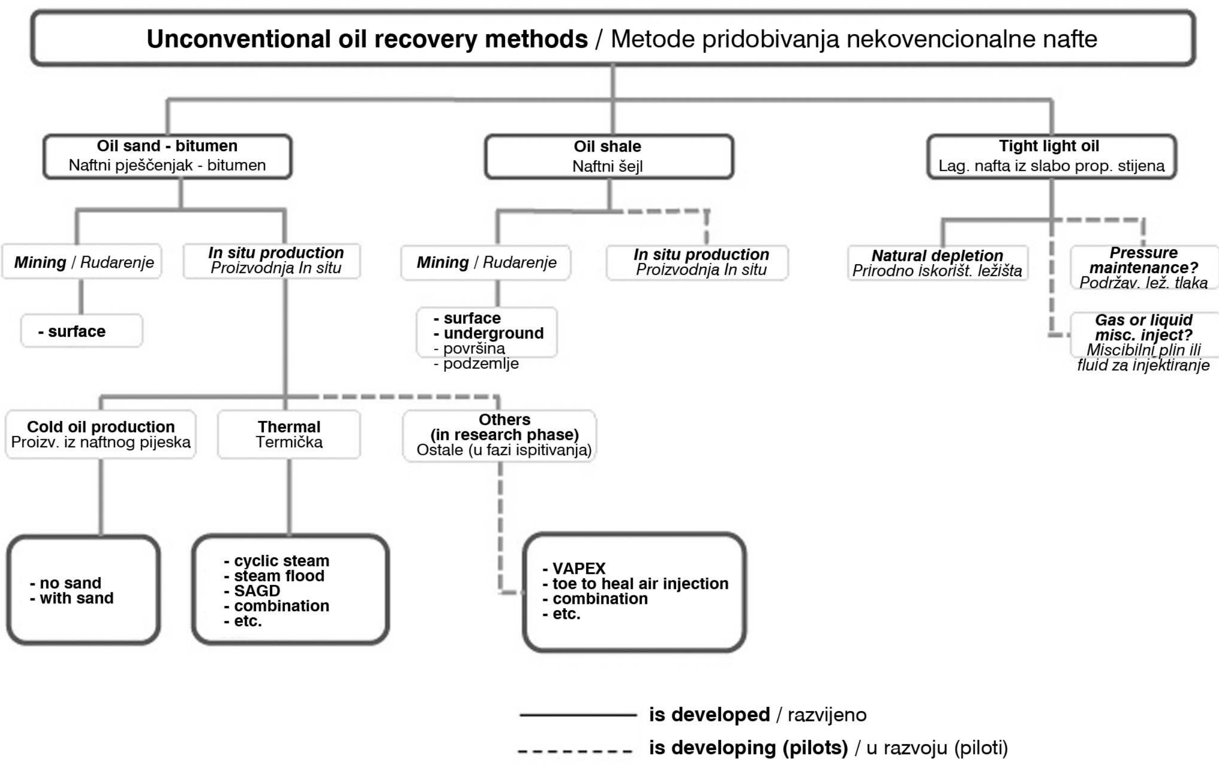

Fig. 2. Unconventional oil recovery methods
Sl. 2. Metode pridobivanja nekonvencionalne nafte

of oil sand-extra heavy oil and oil shale are discussed in the book of Pápay J. (2013). This is why these are not repeated here. The article shows that the tight light oil production is a challenge for petroleum engineers.

The book of Pápay J. (2013)[16] also deals with unconventional gas resources: coalbed methane (CBM), tight gas, shale gas and hydrate resources.

1. Definition and properties

According to Canadian Society for Unconventional Resources (CSUR) tight oil is conventional light oil that is found within very low permeability rocks (sandstones, carbonates and shales). This oil will not flow at economic rate without (e.g.) horizontal drilling coupled with multi-stage fracturing.

Clarkson C.R. and Petersen C.R., (2011)[3] have recommended a classification "Unconventional Light Oil" (ULO) in the following manner, based on Western Canada plays:

Halo Oil: in some existing oil fields, the fringe regions, or halos, surrounding the areas of historical production, are known to contain oil, but with traditional technology cannot produce economically (CSUR). According to the authors, the matrix permeability > 0.1 mD; source is different from reservoir; rock: clastic or carbonate.

Tight Oil: the matrix permeability < 0.1 mD; source is different from reservoir; rock: clastic or carbonate.

Shale Oil: the matrix permeability is (very low) < 0.1 mD; source = reservoir; rock: shale.

It is noted that EIA (2013)[7] uses the term light tight oil in the case where permeability < 0.1 mD, the rock is carbonate, sandstone and shale. EIA uses the terminology shale oil in that case when oil is made from the oil-shale (rock with kerogen) by artificial chemical process (pyrolysis), which can be surface or subsurface (*in situ*) technology.

For example Pápay J. (2013)[16] used the permeability border for tight oil < 1mD, which is based on the accepted tight gas classification (< 0.1 mD) with modification. The modification was due to different viscosity and compressibility of gas and light oil.

In the following text fluid parameters are discussed briefly.

Clarkson C.R. and Pedersen P.K. (2011)[3] used NYMEX definition of light crude oil which includes 32 - 42 °API gravity oil (865-816 kg/m^3).

Clarkson C.R. and Pedersen C.R., (2011)[3] published rock and fluid properties in different cases as examples for Western Canada accumulations, which are presented in table 1.

Simmons D.D. (2012)[23] presented Bakken/Tree Forks play fluid properties, which are as follows:

- oil density is 420 °API (815 kg/m^3) (sweet);
- oil viscosity is 0.3 cP at reservoir condition;
- initial solution GOR 500 to 800 ft^3/bbl (89 – 142 m^3/m^3)
- solution GOR at 3 years production 800 to 1 100 ft^3/bbl (142 – 196 m^3/m^3).

Table 1. Reservoir/fluid properties for Unconventional Light Oil plays in Western Canada

Type of play	Halo oil	Tight oil	Shale oil
Play	Pembina Cardium	Saskatchewan Bakken, Viewfield	Second White Specled Shale
Oil viscosity (cP)	1.36-1.41	0.64	0.64
Porosity (%)	12 (5-12)	12	12
Permeability (mD)	0.28 (0.1-10)	(0.1-10)	
Oil volume factor	1.19	1.22	1.22

Table 2. Major Shale Oil Play Data Comparison

Play	Bakken	Eagle Ford	Niobrara	Utica
Depth (10^3 ft) (10^3 m)	8.5 - 10.4 2.6 - 3.2	4 - 12 1.2 - 3.7	3 - 14 0.9 - 4.3	2– 14 0.6 - 4.3
Thickness (ft) (m)	8 - 14 2.4 - 4.3	300 – 475 91.4 – 144.8	50 – 300 15.2 – 91.4	70-500 21.3 – 152.4
Permeability (mD)	0.05 Middle Bakken	up to 0.13	0.1 – 1.0	0.0003
IP^x(bbl/d) (m^3/d)	200 -1 800 31.8 – 286.2	250 – 1 500 39.8 – 238.5	+/- 600 95.4	1 000 + 6 MMft^3/d (gas) (159 + 170 000 m^3/d) gas
Avg. lateral (ft) (m)	10 000+ 3 048+	5 000 - 7 000 1 524 – 2 134	3 300 – 10 000 1 006 - 3 048	5 500 - 7 500 1 676 - 2 286
Resources (Bbbl) (Mm^3)	5.5 (est. to 20) 874.5 (est. to 3 180)	3.5 556.5	1.5 238.5	3.0 (est. to 5.5) 477.0 (est. to 874.5)

IP = Initial production;
Resources = Technically Recoverable (TRR)
Sonneberg St., A. (2014)[22] estimated the Tight Reservoir General Characteristics
Permeability: <0.1 mD, Porosities: 10%

EIA (2013)[7] published the oil volume formation factors for 28 light tight oil plays whose range is: 1.2 - 2.01; average is 1.51.

According to Baker R. (2013)[1] using EIA data, parameters of some major shale oil play (light tight oil play) are:

2. Practical results

According to NPC (2011)[14], the tight formations, including tight oil accumulations, have been known for decades, usually dating to the earliest exploration efforts within any given basin. The historical background is explained after NPC (2011). Due to conventional technology the economical production of this oil failed. Initial productions (IP) were promising, but after a short time (within some months), significantly dropped. For example, in the Williston basin the Bakken formation was perforated in 1950s and early 1960s. The IP values ranged from 150 to 450 bbl/d (23.9 – 71.6 m^3/d) and typical cumulative production was 85 000 bbl/well (13 515 m^3/well). The early Bakken wells had productive lifetimes of less than 2 to 3 years. After that they become “economically dry”. With horizontal drilling in the early 1990’s IP values increased to 230 to 500 bbl/d (36.6 – 79.5 m^3/d) and cumulative oil production increased to 145 000 bbl/well (23 055 m^3/well), which means that these parameters were “economically not attractive” also.

With improvements in well drilling, completion and stimulation renewed interest in Bakken exploitation. Since 2005 the IP is over 1 500 bbl/d (238.5 m^3/d) and cumulative oil production is estimated at 500 000 bbl/well (79 500 m^3/well). For example, in North Dakota the oil production has increased from 20 300 bbl/d (3 228 m^3/d) (2007) to 220 000 bbl/d (34 980 m^3/d) (2010).

Later, using the multistage fracturing technique (EIA-2014)[8] tight light oil production dramatically increased in the USA: in 2010: 1x10^6 bbl/a (159 000 m^3/a), in 2012: 2.2x10^6 bbl/a (349 800 m^3/a) and in 2013: 3x10^6 bbl/a (477 000 m^3/a).

According to Oil and Gas Journal (03/26/2014), the following three countries have been producing tight light oil. Data are presented in Table 3.

The U.S.A. shale experience (EIA-2013)[7] shows shales are very heterogeneous both aerially and horizontally. According to practical results up to 50% of the fractured stages are not productive, therefore 3 000 - 5 000 ft (914 – 1 524 m) horizontal laterals are employed to have a profitable well. The single well test cannot be used to determine a well's productivity or even the productivity within its immediate neighbourhood. Well production profile and ultimate recovery/well can be quite different (EIA-2013).

Table 3. The production rates of light tight oil in USA, Canada and Russia

Country	Rate		Remark
	10^6 bbl/d	(10^3 m^3/d)	
USA	3.22	512	End of 2013
Canada	0.34	54	2013 average
Russia	0.12	19	2013 average

Table 4. Table shows production decline rate for two different plays

Play	Production rate 10^3 bbl/month / 10^3 m^3/month				Remark production in years		
	initial		actual				
Bakken/three Forks	6	0.953	1.02^x	0.162	1.02^x	0.162	^{x} after 3.5 years
Mississippian	10	1.590	3^x	0.477	3^x	0.477	^{x} after 1.5 year

According to Hart Energy staff report (2014 July pp.112-116), in case of Eagle Ford, only 64% of the clusters are contributing to production. The staff report says (after EIA) that sustained production from a rig point of view is that it takes 2.5 'rig times' to sustain production.

Shale oil wells have only a few years of productions, therefore the statistical method recommends to estimate the future production.

Due to natural depletion the decline rate is very high. This has been presented by some authors.

Baker R. (2013)[1] in case of Pembina Cardium play shows a trend of 81 wells: the initial average rate was 157 bbl/d (25 m^3/d), which decreased to 44 bbl/d (7 m^3/d) after 1 year of production.

Simmons D.D. (2013)[23] shows example wells decline in the Table 4.

Drollas L.P. (2013)[5] presented a typical Bakken well production: q_i = 1 000 bbl/d (159 m^3/d); steep decline in the 1st yr is 65%, in the 2nd yr 35%, in the 3rd yr 15%, and 10% thereafter.

Tight oil's key problem is the rapid decline in well productivity, which requires repeated drilling of wells in order to maintain production - Drollas L.P. (2013).[5]

Recovery factor is a very important technical parameter to characterize the exploitation efficiency.

According to EIA (2013),[7] based on U.S. shale production experience, the recovery factors for shale gas generally ranged from 3 percent to 7% with exceptional cases being as high as 10% or as low as 1%. These data is based on the study of Kuuskraa V.A., Stevens S.C., Moodhe K.D. (2013)[11] prepared for EIA who analyzed 28 U.S. tight oil plays which are producing with natural energy.

It is noted that these recovery efficiencies are based on volumetric estimation of OOIP, which means that the values are only approximations.

According to them 15 - 20% gas saturation is favourable from aspect of oil recovery efficiency.

The other important characterization parameter of the production efficiency is the EUR (estimated ultimate recovery – e.g. m^3/well), which shows whether a well is able to pay for itself or not. This is also an approximation value, because it is usually determined by decline curve fitting.

3. Research to improve the recovery efficiency

For each technical discipline the task is to increase the efficiency: to explore the "sweet spots" (geophysics, geology etc.), to improve the filtration contact between the matrix containing the oil and the well (drilling, fracturing, well completion, etc) and to improve the recovery efficiency based on driving mechanisms (reservoir engineering etc.). The following discussion takes into consideration only the view points of reservoir engineering.

3.1 Driving mechanisms and relative permeability functions

As it was discussed in case of natural depletion due to low matrix permeability the recovery factor is low or

Table 5. The reservoir rocks properties from Upper, Middle, and Lower Bakken

Formation	Porosity (%)	Permeability (mD)	Remark
Upper Bakken	?	?^{x}	?^{x}(very low)
Middle Bakken	4.5 - 8.1	0.002 - 0.04	
Lower Bakken	?	?^{x}	?^{x}(very low)
Conventional rock	25	800-1100	

Note: Upper and Lower Bakken have much lower permeabilities than Middle Bakken.

moderate. Most likely the driving mechanism is compaction with moderate internal gas drive (and/or moderate water drive?).

It should be cleared up whether the "permeability jail" (law of Masters J.A. -1979)[12] concept or percolation theory (Pieters D.A., Graves R.M.-1994) works or in what conditions it is valid (e.g. Pápay J.-2013)?[16]

According to some well measurements the two phase flow often occurs in low permeability rocks: e.g. Shanley K.W., Cluff R.M., Robinson J.W. -2004 (water-gas),[21] Eberhard M. 2010 (water-oil),[6] or Clarkson C.R.[3], Petersen P.K. - 2011(oil-gas). This is very important from the aspect of relative permeability functions which are the basis of production prediction (e.g. Pápay J. 2003, 2013).[15,16]

3.2. Laboratory measurements

Below is given a short summary to show that hard work and research is ongoing to understand the recovery mechanisms of tight light oil production. The conclusions will likely be the hard topic of discussions due to early phase of research.

3.2.1. Standards for characterization of rock properties

E.g. Bertoncello A., Honarpour M.M. (2013)[2] recommend the laboratory measurement process standards to determine the basic parameters – porosity, permeability – of the unconventional rocks (shale).

3.2.2. Spontaneous imbibitions

E.g. Morsy S., Sheng J.J... (2013)[13] completed laboratory measurements to understand the role of spontaneous imbibitions to enhance the oil recovery from shales. According to them water flooding has a great potential.

3.2.3. Gas injection

Harju J. (2012)[9] has given an account of CO_2 injection (pilot) program in case of Bakken accumulation within the frame of work of Energy and Environmental Research Center (EERC) at the University of North Dakota.

Hawthorne St.B., Gorecki Ch.D., Sorensen J.A., Steadman E.N, Harju J.A., Melzer St (2013)[10] discussed the light oil mobilization mechanism from Upper, Middle, and Lower Bakken reservoir rocks with CO_2 injection by laboratory measurements.

The experimental pressure was 5 000 psi (345 bar) and temperature 230 °F (110 °C). Typical reservoir rock geometrical parameters for measurements were: 3 x 9 x 9 mm chicklets; 9 x 9 x 30 mm sq rods and 10 mm diameter rods. In case of Upper and Lower Bakken the rock was milled into < 3.5 mm fragments. The oil saturated rock samples were not sealed to the wall of equipment, so CO_2 flows around the pieces of rock samples.

Two types of experiments were realized:

- initial 96 hour exposures with static extraction (non flowing CO_2),
- recovery under flowing CO_2 (dynamic conditions).

Their conclusions were:

- oil recovery is high even from very tight source rock shales, but takes a very long time;
- high surface area greatly enhances the rate of recovery;
- mobilization of light oil components into CO_2 is a dominant recovery process rather than dissolution of CO_2 into the bulk of oil;
- speculation on the exact mechanism based on this experiment is difficult.

Tovar F.D., Eide O. Graue A., Schechter D.S. (2014)[24] also conducted laboratory experiments using CO_2 injection in case of sidewall core samples with negligible permeability. According to them carbon-dioxide is a promising agent to enhance the low recovery of natural depletion. According to their measurements vaporization of the hydrocarbons into CO_2 is a main recovery mechanism. They concluded: more work is required to better understand the role of different phenomena when CO_2 is exchanging mass with the oil resulting in additional recovery.

Rassenfoss St. (2014)[19] gives a summary, up to end of 2013, about research work that has been completed to enhance light tight oil recovery in US.

According to him:

- carbon dioxide may offer an unconventional EOR option for enhancing the recovery;
- on the basis of early tests, using chemical surfactants showed a positive result (Texas A&M University laboratory measurements);
- many unconventional reservoirs including Bakken are oil-wet, which means the
- water flooding is very unlikely to succeed (after Ed Steadman);
- two CO_2 "huff and puff" experiments were completed but were not successful (after Harju J.)[9].

3.3. Difficulties to estimate production rates

Due to low (matrix) permeability:

- both the injection and production wells should be fractured. The fracture nets generally are random (unknown) which means that regular displacement front cannot be easily formed which may result in low volumetric sweep,

Table 6. Proved light tight oil reserves in USA, Saudi Arabia and Russia

Countries	Oil		Gas	
	10^9 bbl	10^9 m^3	10^{12} ft^3	10^{12} m^3
USA	31	4.9	393	11.1
Saudi Arabia	268	42.6	290	8.2
Russia	80	12.7	1 688	47.7

- the conventional material balance equation cannot be used to determine the OOIP, driving indexes etc,
- filtration models (e.g. numerical) are only approximations because the fluid-rock interaction functions (relative permeability curves etc.), parameter distribution etc. are not known and therefore the risk (high, reference, low case) and sensitivity analyses (Tornado diagram) are recommended for well or section modelling.

4. Significance of light tight oil production, economics

EIA (2014)[8] says that by 2015 USA will be top oil producer in the World surpassing both Russia and Saudi Arabia due to light tight oil production. At the same time it has to be emphasized that the proved reserve/annual production parameter for USA is much lower than for the two others. According to EIA (2013)[7] the proved reserves (Internet) are shown in Table 6.

It is noted the supply prices are also quite different for these countries. Because of high productivity of Saudi Arabia wells, her supply cost is the lowest among the countries.

The estimation the light tight oil production in US, according to EIA (2014)[8] is presented in Table 7.

In low and reference case in 2016 - 2018 the total oil (conventional + unconventional) production of U.S. will peak as high as it was in 1970 - 1971 (~ 10 x 10^6 bbl/d; (1.59x10^6 m^3/d). In the high resource case the total oil production will be as high as 13.5 x 10^6 bbl/d; (2.147 x 10^6 m^3/d) (peak) by 2040. In the reference and low case, the tight light oil production in USA decreases the share of oil import by 12 - 13% as an average. Oil import in this time frame (2013-2040) is 28-33%. In the high case, oil imports gradually decrease to 0 by 2036.

According to EIA report (2013)[7] – prepared by ARI the estimated technically recoverable shale gas and (shale) tight oil in case of 41 countries (including USA) for 95 basins and for 137 formations is as follows:

Technically recoverable resources, including U.S.

- Shale gas 7 299 x 10^{12} ft^3 (206 x 10^{12} m^3)
- Shale/tight oil 345 x 10^9 bbl (54.9 x 10^9 m^3)

United States

- EIA shale / tight shale gas proved reserves 97 x 10^{12} ft^3 (2.7 x 10^{12} m^3)
- EIA shale / shale gas unproved resources 567 x 10^{12} ft^3 (16 x 10^{12} m^3)
- EIA shale / tight oil unproved resources 58 x 10^9 bbl (9.2 x 10^9 m^3)
- Increase in total resources due to inclusion of shale oil 11%, shale gas 47%
- Share as a percent of total shale oil 10%, shale gas 32%

B. Rodgers (2013)[20] provided an assessment of the economics and fiscal competitiveness of the major tight oil plays in USA and Canada. He estimated oil supply prices assuming different well production profiles and well types with respect to EUR in different tight oil plays in case of USA (number of plays: 15), and in case of Canada (number of plays: 11)

The calculated supply prices are in Table 8.

This means that these supply costs correspond with regard to oil sand and extra heavy oil production (e.g. Pápay J. -2013),[16] and that the two types of oil compete with each other on the market.

According to EIA (2014)[8] a potential shale well that costs twice as much and produces half the output of a typical US oil well would be unlikely to back out current supply sources of oil or natural gas. It means that costs of light tight oil are approximately four times more expensive than costs of conventional one in USA.

Conclusions

- an overview is given about the tight light oil production from the aspect of petroleum reservoir engineering;
- at present the recovery process is natural depletion, resulting in a modest recovery factor;
- research is ongoing to enhance the exploitation efficiency;
- light tight oil production is a challenge for petroleum engineers;

Table 7. US light tight oil production forecast

Resources cases	Cumulative 2012-2040 years		Peak rate		Peak year
	10^9 bbl	10^9 m^3	10^6 bbl/d	10^6 m^3/d	
High	75	11.9	8.5	1.4	2035
Reference	44	7.0	4.8	0.8	2021
Low	34	5.4	4.3	0.7	2016

Table 8. The calculated supply prices in USA and Canada

Country	Range		Average	
	USD/bbl	USD/m^3	USD/bbl	USD/m^3
USA	36-92	226 - 579	65	409
Canada	48-70	302 - 440	56	352

- in the near future the tight light oil production will most likely contribute to supply a great part of the primary energy consumption of the World.

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