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THE USE OF COMPUTER SIMULATIONS TO ASSESS THE EFFECTIVENESS OF THE REVITALIZATION OF MATURE OIL FIELDS USING THE SELECTED RESERVOIR AS AN EXAMPLE***

1. INTRODUCTION

The decrease in new oil field discoveries over the years makes it necessary to return to the abandoned and partially depleted oil fields. Due to remaining significant amount of geological resources, mature oil field are seen as a valuable global resource and can be important in the overall balance. Generally, mature fields are fields that are in a state of declining production or reaching the end of their productive lives. Revitalizing them means taking measures that increase the value of hydrocarbons extracted from the field. Thanks to various recovery methods the production rate can be increased and significant amounts of resources can be extracted. Every field has a specific production curve over which production grows to a peak level and then declines until it reaches the point at which operation is no longer economic. Revitalization extends the natural decline curve to provide an economic profits from hydrocarbon production [1, 6].

The article indicate the role of computer simulation as a tool in planning process of revitalization works in case of mature oil fields exploration and management. Methods of revitalizing mature oil fields used in Poland and wide world were briefly presented. A recovery methods are proposed, using computer simulation for the selected reservoir in south – eastern Poland as an example. The effectiveness of the recovery method is determined through forecast of future production. An preliminary economic analysis

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would be performed to determine the feasibility of the selected method taking into account the initial investment costs and different oil prices.

2. ROLE OF RESERVOIR SIMULATIONS

As a tool to design redevelopment plan for mature oil fields and their further management reservoir simulations can be involved. High investment costs related to redevelopment of mature fields makes that numerical simulations are the cheapest and safest way to test different variants of production strategy [7, 8]

Reservoir simulation is the means which uses a numerical model of the petrophysical characteristics of a hydrocarbon reservoir to analyze and predict fluid behavior in the reservoir over time [4]. Numerical reservoir simulation consist of creating a virtual model of the real field which is divided into lots of parts (blocks) by three-dimensional net. Every grid block is characterized by its own petrophysical parameters such as permeability, porosity as well as dynamic parameters such as fluid saturation and pressure. This parameters are dynamic because they are changing in time during the simulation. Every grid block involves solving large sets of simultaneous partial differential equations, which states the mathematical model, to estimate transient, multiphase or multicomponent flow in heterogeneous media [10]. One of the most important equations is continuity equation and principle of mass conservation. All mathematical equations describe with some approximation phenomena occurring in the real reservoir. Indispensable elements of reservoir simulations are initial and boundary conditions as well as limitations referring the specified problem.

The most important tasks of reservoir simulation used in redevelopment of mature fields are:

- choose the best solution among the possible and tested production strategies,
- production forecast, process optimization and establish basic operating parameters,
- estimate the probable time of further production,
- estimate recovery factor,
- obtain the necessary data for the preliminary economic analysis.

Using of numerical simulation for petroleum reservoirs was initiated in 1950's and it is developed constantly. Nowadays this is a key method for planning, development, management and optimization of hydrocarbons production [4].

3. METHODS OF REVITALIZING MATURE OIL FIELDS

In order to better extraction of hydrocarbons from mature field, it is necessary to prepare the plan for its revitalization. Revitalization can be done in different ways, which can be classified in two groups. The first of them is referring to production wells and include such treatments as recompletion of existing wells, optimization of oil lift, well stimulation treatments that improve contact with the reservoir (e.g. hydraulic fracturing, matrix acidizing), infill drilling or perform horizontal wells. The second way is to act directly on the reservoir in order to increase the pressure and improve the mobility of the fluid. This method involves use of secondary and enhanced oil recovery methods (EOR). Depending on the type of a field, petrophysical and fluid properties, history of its production, we can choose one of the above methods, or use both at once. Every hydrocarbon reservoir is specific so it is important to consider all available method and choose properly one of them, following by the criteria of selection the optimal revitalization method [1]. Figure 1 shows the general distribution of revitalization methods.

Impact through production and injection wells:

- Secondary methods:
  - Water flooding
  - Gas injection
- Enhanced oil recovery (EOR):
  - Miscible gas injection (CO_2, N_2)
  - Thermal methods
  - Chemical methods
  - Microbiological methods

Impact through production wells:

- Infill drillings
- Well stimulating
- Well recompletions
- Optimization process of oil lift

Fig. 1. Methods of revitalization mature oil fields

4. DESCRIPTION OF THE MODELED RESERVOIR

The analyzed reservoir is located in the south-westerly edge of the East European Platform in the central part of the Lublin trough – the south-eastern Poland. The total area of the reservoir is about 58 hectares. The terrain is flat and plains with an average height of 157.5 AMSL. Industrial resources of hydrocarbons have been deposited within anticlinal and eroded part of the upper Devonian (Fammenian). The reservoir rock is formed by fine-grained quartz sandstone with inserts of mudstone. Documented deposit thickness is in the range of 4 and 8,5 m. The lower border of the reservoir determines oil water contact was assumed at the depth –2146,5 AMSL.

The petrophysical properties of the reservoir rock, such as porosity and permeability were determined on the basis of measurements from well logging and well testing as well as laboratory analysis of core samples. The determined porosity is in the range from 1.67% to 9.2% and its average value is 5.78% The permeability was determined by a well test made in the well X-1 and the analysis of the bottom hole pressure rebuilt curve using Horner methodology. The mean value of permeability was estimated on 1.059 mD. In drilling cores samples have been found numerous, multidirectional fractures of rocks what indicate on the dual permeability character of the reservoir. Based on well logs the mean oil saturation of the pore space has been determined on 55%.

In the area of the reservoir was drilled a total of 8 wells whereby it was possible to recognize the geological structure. The significant production was achieved only by first productive well X-1 drilled in 1991. At the beginning the well produced self dependently and then it was reconstructed for pumping system which works till now. Production of oil to a small extent took place also by two others wells X-2 and X-3 but during well tests they have not achieved industrial production. For this reason the wells have been liquidated.

In the early years of production, the primary factor provided the reservoir energy was gas dissolved in the oil. It allowed for self-exploitation well X-1. Currently, the conditions for the reservoir energy can be described as mixed, where still the largest share has the expansion of the gas dissolved in oil. An important factor of energy is also the expansion of the rock and reservoir fluids. In recent years, small part of the energy system of the reservoir is also the underlying water which flows in small amounts to the well. Factor gravity is negligible, due to the geometry of the bed and the low permeability of the reservoir rock.

Primary geological resources of oil and associated gas were calculated using static method which was based on analysis of the natural decline curves considering the historic production data. To the end of 2013 there have been extracted only 16,2% of geological resources of crude oil and 19,3% of associated dissolved gas.

5. SIMULATION MODEL

Static model

Data for the static model are generally provided from geology, geophysics, seismic as well as laboratory measurements of rock samples. The more information the better quality of model [9]. The modeling workflow starts from the structural modeling, which builds faults and horizon surfaces as the skeletons or frames for the models. Property modeling is used mainly to populate the structural models with lithologies, petrophysical properties or fluid saturation using well log interpretations which are up scaled to the models. Building of the structural model was performed in the depth domain on the basis of structural map of the top of upper Devonian – Figure 2.

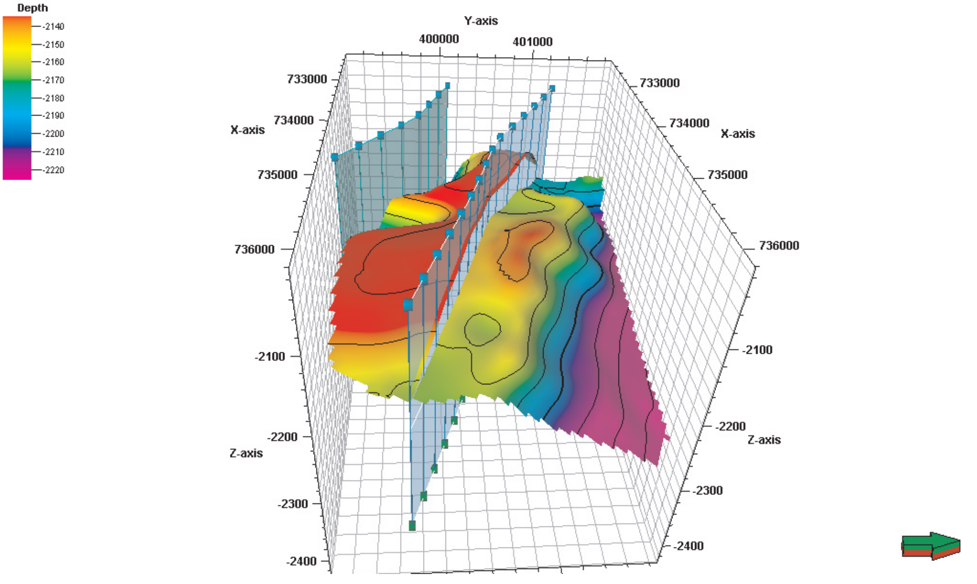

Fig. 2. The roof of the upper Devonian in 3D view

After pillar gridding procedure and horizons generation, layering process was applied. These layers, in conjunction with the pillars, define the cell of the 3D structural grids that are assigned petrophysical properties during property modeling. Figure 3 illustrates result of spatial porosity modeling.

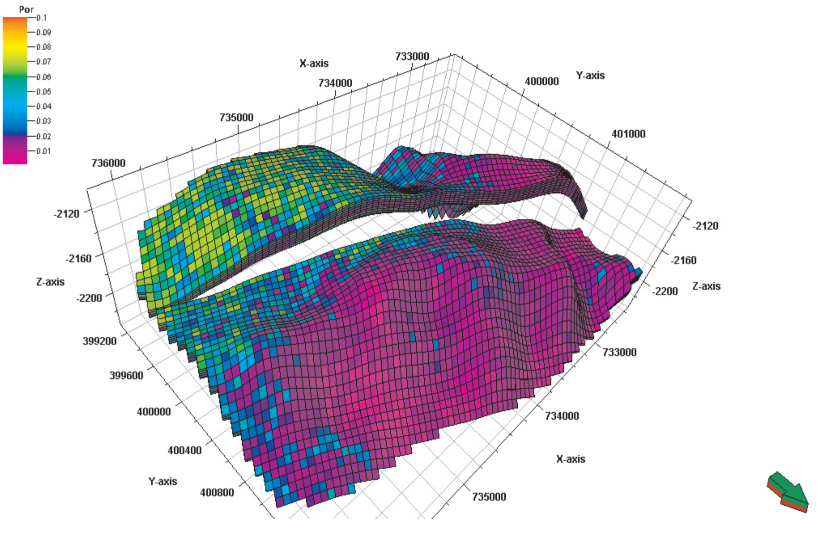

Fig. 3. Spatial distribution of porosity

Dynamic model

The static model was built as an input for flow simulations (dynamic models) to predict production profiles. Due to the simple nature of the problem it was defined "Black oil" type of model which involves defining only each phase without defining individual components. In order to define dynamic model of the reservoir it was necessary to establish following parameters:

- physical properties of fluids (oil viscosity and volume factor in the pressure function, gas viscosity and volume factor in the pressure function),
- relative permeability of oil water and gas for the rocks,
- fluids and rocks compressibility,
- initial conditions (depth of oil-water contact, initial pressure and capillary pressures).

These parameters were established on the basis of geological documentation of the reservoir.

Scale up static model

It is common for dynamic modeling to scaled up the very fine scale geological model which is frequently too big (more than 10 mln cells) for numerical calculations. It could take a long calculations time and cause the risk of the numerical approximation errors. Dynamic model should contains about 1 mln active cells. In this case it was not necessary to make scaling up because geological model contains about 15 000 cells and this step was skipped.

History matching

The next stage after building static and dynamic model is its calibration. History matching consist in matching the pressure and rates of reservoir fluids obtained during the simulation to the data recorded during the history of reservoir production. In summary it is imitate history of the reservoir work on the built model [9]. The model has been calibrated using historic production data i.e. rates of oil water, gas and periodic measurements of bottom hole pressure. There was set up the average monthly oil rates on the basis of which the simulator Eclipse 100 calculated rates of water and gas as well as changes of reservoir and bottom hole pressures. In case of divergent simulation results and historic production data it is necessary to back to static or dynamic model and correct some petrophysical parameters or fluid and rock properties. Below is presented results of history matching process – Figure 4.

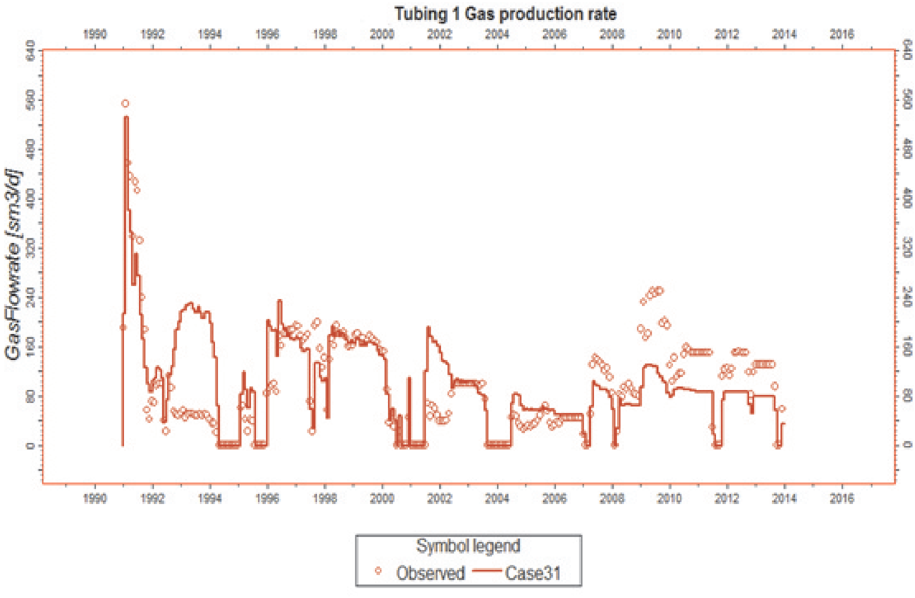

Fig. 4. Gas production rate – results of history matching

6. REVITALIZATION PLAN FOR MATURE OIL FIELD

After analysis the petrophysical parameters of the reservoir and physical properties of fluids, the discussed reservoir in most cases did not meet the criteria that would allow the use of revitalization through injection wells methods such as water flooding, gas injection or enhanced oil recovery methods. It is mostly caused by poor characteristics of porosity and permeability of reservoir rock. Moreover, using one of these methods is also connected with the necessity of drilling new wells. It is a significant investment which probably would never pay off due to the modest reserves of deposit possible to extract. In this case, the redevelopment plan should be focus on the revitalization by interaction via existing production well X-1. In order to increase the production rate the following options are proposed:

a) Stimulation of production well X-1 by hydraulic fracturing

Increasing the efficiency of the oil extraction can be obtained by performing stimulating operations on the well such as acidizing or hydraulic fracturing. Hydraulic fracturing involves the high-pressure injection of ‘fracking fluid’, containing water and sand or other proppant, into a wellbore to create cracks in the deposit formations. This results in significant increases permeability of the rock [2, 3].

There was assumed that as an effect of hydraulic fracturing will be created a fracture of 100 m length. Based on an assumed type of proppant used to fracturing there was calculated improvement of permeability near the area of the well. The average permeability of blocks involved by the hydraulic fracturing treatment increased in the X direction about 3 times. Improvement of fractured area is presented on Figure 5.

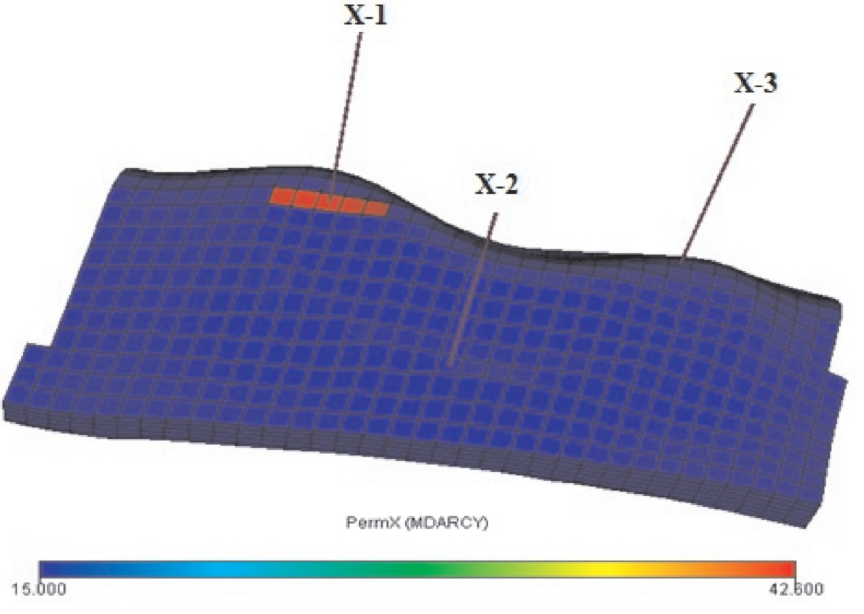

Fig. 5. Influence of hydraulic fracturing on reservoir permeability

b) Reconstruction of production well X-1 by drilling horizontal branch – 500 m length

Another option is to reconstruct the existing well X-1 and perform a horizontal branch. From the existing vertical well it is done a section of directional or horizontal branch, which allows to share a large part of the reservoir without drilling new vertical wells. The length of proposed branch is 500 m and trajectory comes towards the center part of the reservoir. It starts at a depth of 2296 m, and extends upwardly into reservoir layer. The trajectory of the proposed reconstructed well is shown in Figure 6.

c) Reconstruction of production well X-1 by drilling multilateral branches using coiled tubing technology

In recent years, technology has developed in drilling 'slim hole' wells which aimed at the reduce the cost of drilling. Drilling with use of coiled tubing technology depend on drilling a branch with use a flexible pipe on a portable device. It is not necessary to fix independent drilling rig. Thanks to this 'slim hole' drillings are from 30% to 50% cheaper compared to the conventionally drilled wells. This technology works on especially on mature fields where drilling new wells does not pay off. It is also possible to perform several horizontal or directional wells from one vertical well [5]. One of the concept of increasing oil recovery factor from described reservoir is to perform three ‘slim hole’ multilateral branches using coiled tubing technology. Each branch has 50 m length. This would considerably save costs of the investment. The directions of performed holes are shown on Figure 7.

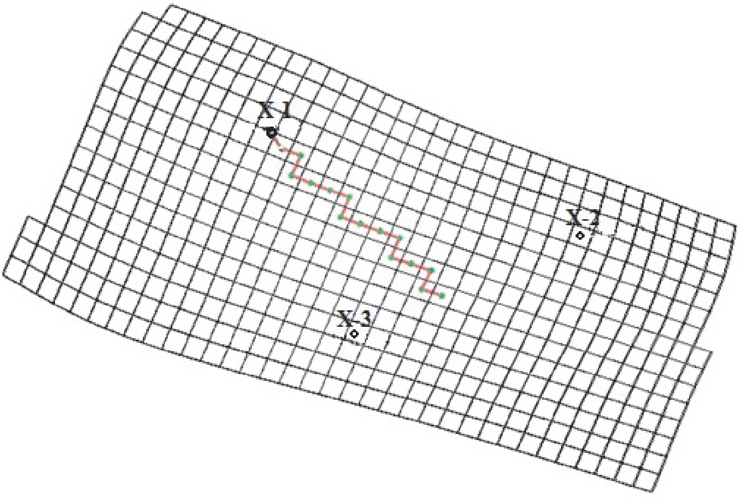

Fig. 6. Reconstruction of well X-1 by drilling horizontal branch – 500 m

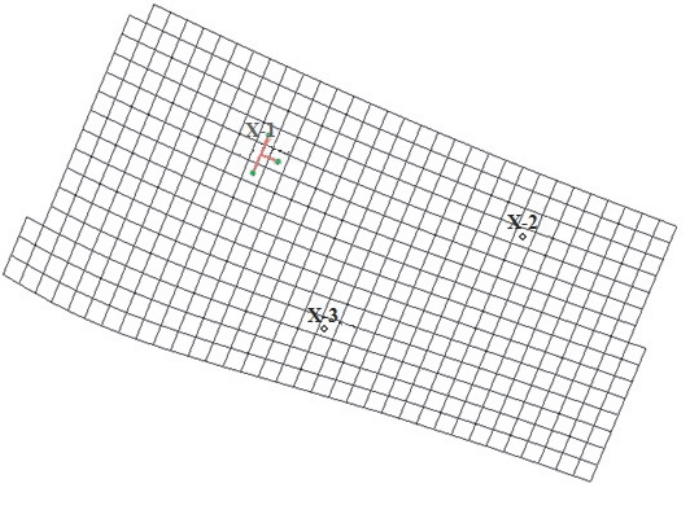

Fig. 7. Reconstruction of well X-1 by drilling multilateral branches using coiled tubing technology

d) Reconstruction of production well X-1 by drilling horizontal branch – 500 m length and drilling new horizontal well X-4 with the length 200 m of horizontal segment

The last proposed solution assumes to perform two horizontal well. The fist one is the horizontal branch from well X-1 described in point b and the second is a new well horizontal well drilled from the other side of the reservoir. The length of horizontal segment is 200 m. This case cause that the deposit will be better shared for sure but cost of the investment will increase considerably. This solution is shown below (Fig. 8).

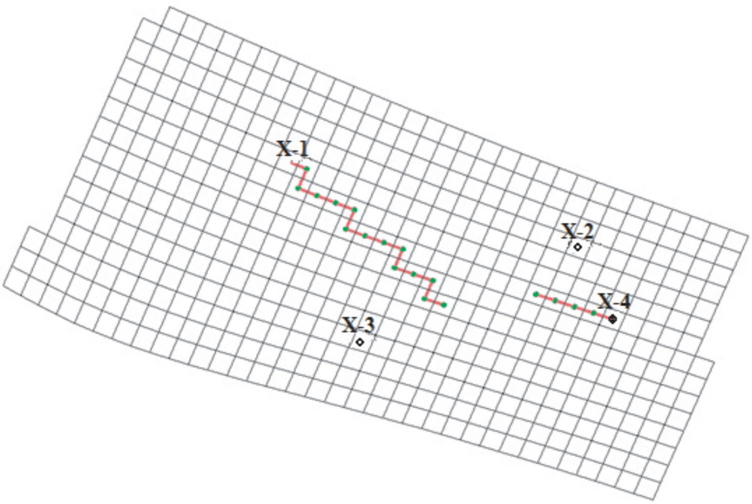

Fig. 8. Two horizontal wells

7. THE RESULTS OF PERFORMED SIMULATIONS

Simulations of all production forecast methods mentioned above were conducted using the numerical simulator ECLIPSE 100. Production has been established for 16 years since the beginning 2014 until the end of 2029. In order to compare the effectiveness of the proposed concept of redevelopment, in addition, it was carried out the simulation of the reservoir production without changing construction of existing well X-1. The main results of simulation are presented in Table 1 and Figure 9.

The results of numerical simulation show that the greatest oil recovery factor is obtained using methods with two horizontal wells – 35,43%. The next one are reconstructions of existing well by drilling horizontal segment and perform three multilateral 'slim hole' branches with coiled tubing technology. Hydraulic fracturing have not brought significant improvement of oil production. As might be expected further production with no redevelopment of the exploitation system gives the smallest increase of oil extraction during 16 years of prediction.

Table 1
Results of simulation

Conceptions of redevelopment plan	Oil production total [$\times 10^3$ m^3]	Gas production total [$\times 10^6$ m^3]	Recovery factor [%]
Two horizontal wells (a)	30.65	4.18	35.43
Horizontal branch – 500 m (b)	27.33	4.00	31.90
Multilateral well – CT (c)	20.92	2.93	24.42
Hydraulic fracturing (d)	19.07	1.99	22.26
Production without changes (e)	17.91	1.56	20.90

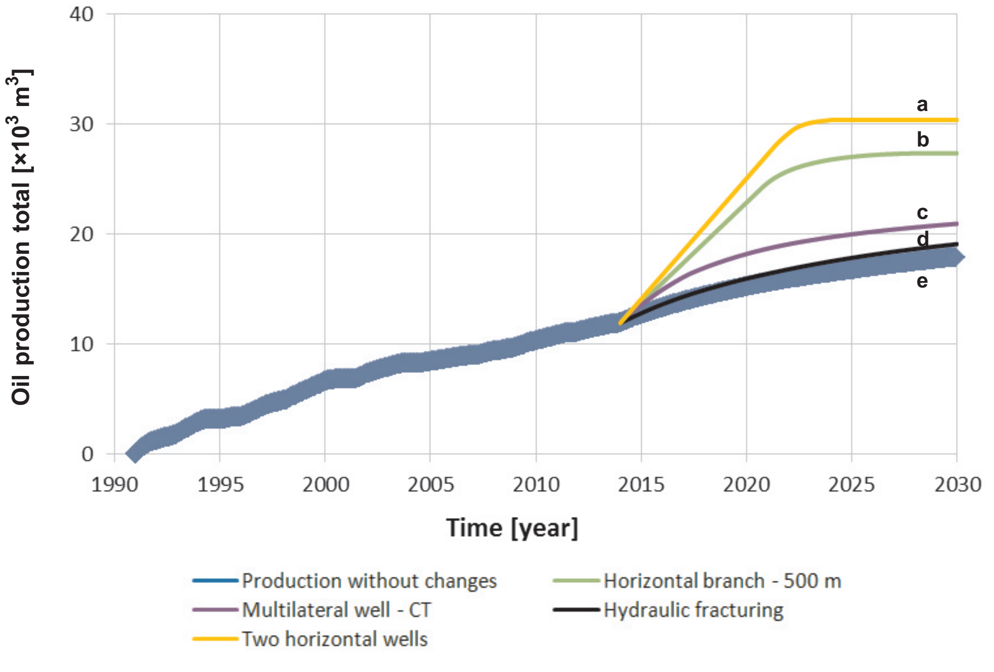

Fig. 9. Oil production forecast

8. PRELIMANARY ECONOMIC ANALISYS

For the preliminary economic analysis of the proposed revitalization concepts of the reservoir, as a measurement of the profitability of investments there was assumed net present value – NPV. Analysis time corresponds to the duration of the simulation.

The analysis was carried out taking into account the initial costs that must be incurred to perform each of described variants, income from the oil sales and the oil prices. The calculation excluded the fixed costs such as costs of produced brine utilization.

The following equation were used:

$$NPV = \sum_{t=1}^{n} \frac{CF_t}{(1+r)^t} - I_o \tag{1}$$

where:

- NPV – net present value,
- CF_t – the net cash flow,
- r – the discount rate,
- t – the time of the cash flow,
- I_o – initial investment cost.

Initial costs of investments and values of parameters used in calculations are shown in Table 2.

Table 2

Parameters of preliminary economic analysis

The cost of hydraulic fracturing (variant a)	3 000 000 PLN
The cost of horizontal branch – 500 m length (variant b)	8 000 000 PLN
The cost of multilateral branches using CT technology (variant c)	1 000 000 PLN
The cost of two horizontal wells (variant d)	24 000 000 PLN
GPB-PLN exchange rate	3.65
The rate of income tax	0.19
The discount rate	0.05

The results of preliminary economic analysis are shown in Figure 10.

The chart of value NPV as a function of oil prices is linear function due to the constant value of the assumed discount rate and the dollar price. Based on this analysis it can be conclude that at the low price of oil (below 20 $/bbl) the considered concepts are not profitable (point 1). Between 20 $/bbl and 74 $/bbl the best solution is multilateral well performed the coiled tubing technology (point 2). When the oil price is higher than 74 $/bbl the most beneficial method is to perform horizontal branch of 500 m length from the existing well. Despite of the fact that the last concept with two horizontal wells allows to extract the largest amount of resources, this variant pay off only at the oil price higher than 105 $/bbl (point 3). It is because a very high costs of initial investment. Hydraulic fracturing is not remunerative at the whole analyzed range of oil prices.

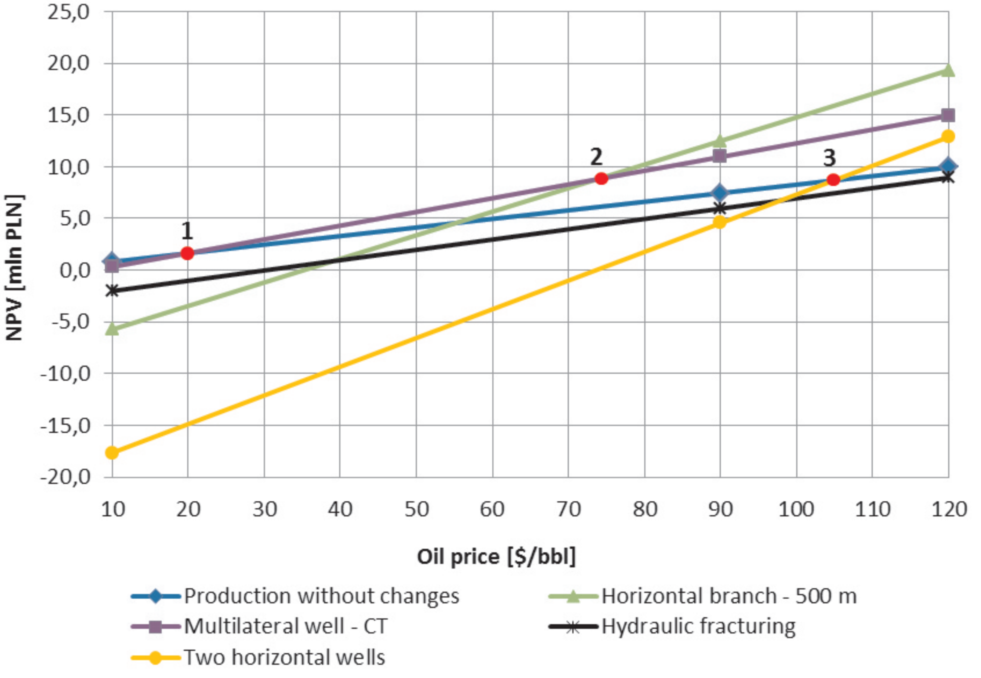

Fig. 10. Results of preliminary economic analysis

9. CONCLUSIONS

Mature oil fields over the years of its production, have been well recognized. A lot of detailed geological, geophysical and petrophysical information have been collected which allows to create an accurate spatial, structural model. A long period of production deliver us an information about physical phenomena occurring in the deposit as well as fluids and rocks properties. It enables to match the model and make production forecast more reliable.

As the example show each operation on the field entails considerable investments so it is extremely important to conduct a precise economic analysis and consider various opportunities of redevelopment. Simulation studies concerning revitalizing methods of mature reservoir are the best way to avoid making suboptimal and costly decisions. It helps to select the most profitable redevelopment option, locate production or injection wells and set up optimal parameters of their work. The vast amount of information about the mature field makes that they are perfect object to built their numerical models.

REFERENCES

[1] Babadagli T.: *Development of mature oil fields. A review*. Journal of Petroleum Science and Engineering, 2006, pp. 221–246.

[2] Gandossi L., Estorff von U.: *An overview of hydraulic fracturing and other formation stimulation technologies for shale gas production – Update 2015*; EUR 26347; doi: 10.2790/379646.

[3] Kasza P.: *Zabiegi hydraulicznego szczelinowania w formacjach łupkowych.* NAFTA-GAZ, nr 8, 2011, pp. 874–883.

[4] Lie K.-A.: *An Introduction to Reservoir Simulation Using MATLAB*. SINTEF ICT, Department of Applied Mathematics Oslo, Norway, 2015.

[5] Miziołek M.: *Wiercenia otworów typu slim hole na świecie i możliwości zastosowania ich na obszarze zapadliska przedkarpackiego i Karpat.* NAFTA-GAZ, nr 12, 2014, pp. 908–9017.

[6] Parshall J.: *Mature Fields Hold Big Expansion Opportunity.* SPE 1012-0052 JPT, 2012.

[7] Rychlicki S., Stopa J., Wojnarowski P.: *Możliwości rewitalizacji złóż ropy naftowej*. Wiertnictwo Nafta Gaz, t. 25, z. 1, 2008, pp. 43–50.

[8] Rychlicki S. (ed.): *Możliwości zwiększenia efektywności wydobycia ropy naftowej ze złóż Karpackich*. Wydawnictwa AGH, Kraków 2010.

[9] Rychlicki S. (ed.): *Metody usuwania zanieczyszczeń węglowodorowych ze środowiska gruntowo-wodnego*. Uczelniane Wydawnictwa Naukowo-Dydaktyczne AGH, Kraków, 2006.

[10] Thomas G.W.: *The Role of Reservoir Simulation in Optimal Reservoir Management*. SPE 14129, 1986.