IOP Conference Series: Earth and Environmental Science

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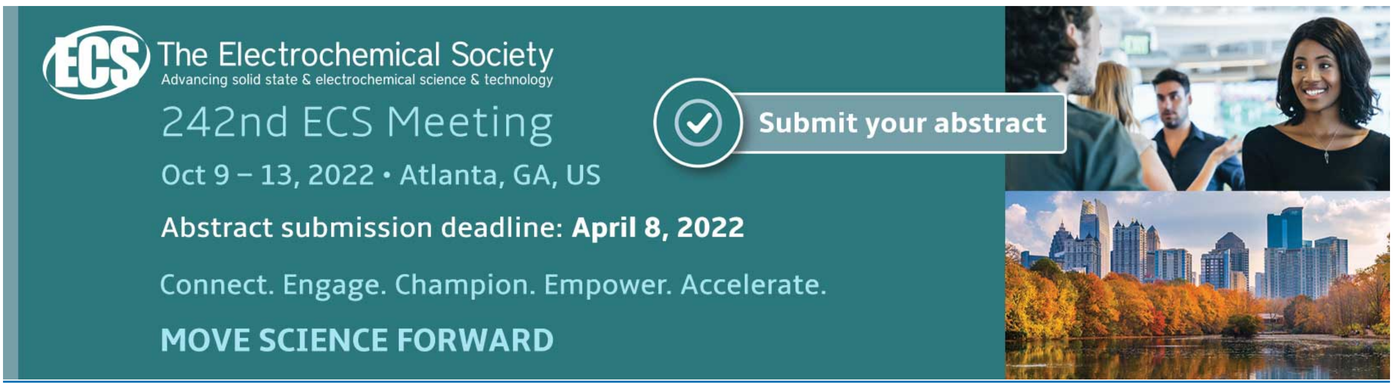
To cite this article: A S Lukyanov 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **988** 032019



IOP Conf. Series: Earth and Environmental Science **988** (2022) 032019 doi:10.1088/1755-1315/988/3/032019

Identification of the Shale Production Model

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Abstract. The technique of appraisal have been proposed for the evaluation of the recoverable reserves according to production schedules for the total wells number of the same calendar year into operation. *NPV* formula representation and necessary conditions for optimality have been proposed. Recoverable reserves and rate of production (production decline) have been identified for the wells put into operation in 2012 – 2017. As a trend, the initial production rate of wells and recoverable reserves grew from year to year, as well as investments in one well. The ties between the length of horizontal wellbores multiplied by the volume of injected proppant and production parameters have been studied. The choice of production technology depends on the actual oil price. With an increase in the oil price, optimaly coordinated increase both the recoverable reserves and the rate of production at the well.

1. Introduction

In [1], the task is to determine the recoverable reserves of shale deposits. Paper [2] has plots showing actual data for shale production. This allows for the identification of the mathematic model parameters [3]. These plots are digitized in increments of 1 month. Plots were digitized in the Paint software with the use of integrated vertical and horizontal rulers with 1-pixel scale intervals.

2. Oil production free fall model

The theory is that the production of a single shale hydrocarbon well is at its maximum on the first day (month) after its putting into operation. If the production method remains the same, it leads to a production-free fall in the future. For total wells production, which has been put into operation during the same calendar year, free fall starts at the end of the current calendar year.

Each plot shows data for wells put into operation during the same calendar year (2012-2018). The model assumes that the wells are put into operation evenly throughout the year. Each point on the plot represents overall month production, divided by the number of producing wells (at the end of the month), divided by the number of days in the months q_f.

Let's plot a free fall trend for the production schedule [2] of the wells put into operation in 2012 – 2017 years.

To implement that, we shall plot logarithmic plots $\ln(q_f)$ starting from the 13-th month after putting the first well into operation, i.e. since the moment of the free fall beginning for all the wells of this calendar year. Let's use EXCEL instruments to plot linear trends of these plots (figure 1).

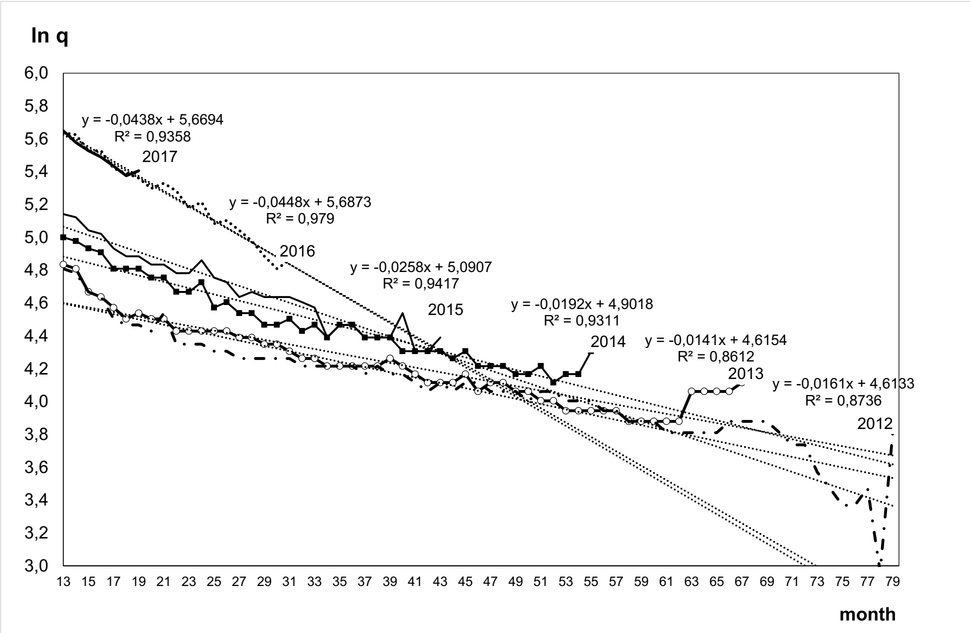

Figure 1. Trends of production logarithms, their formulas and dispersion index R^2

As for wells put into operation in 2014 – 2017, the linear trend on a logarithmic scale closely corresponds with actual data (R^2 > 0.93). For wells put into operation in 2012 – 2013, this correspondence is worse (R^2 > 0.86).

Let's build an exponent from the formula

$$y = -mx + q, \quad q(t) = q(12) \cdot e^{-m(t-12)}, \quad t \geq 12, \tag{1}$$

where $q(12)$ – average production rate at the year's end [BOE/day], t is measured in months, and production decline parameter m is in units per month. The trend parameters (1) are shown in Table 1, where $V(12)$ – estimates of residual recoverable reserves.

Table 1. Parameters of production free fall trends.

Year of putting into operation	Production rate at the year's end, BOE/day	Production decline m, %/month	Production decline m, %/year	m_y per year	$V(12)$, thous. BOE
2012	100	1.6%	19%	18%	189
2013	100	1.4%	17%	16%	217
2014	133	1.9%	23%	21%	211
2015	160	2.6%	31%	27%	189
2016	289	4.5%	54%	42%	196
2017	284	4.4%	53%	41%	197

Production rates at the year's end significantly lower than maximum actual production rates. It means that production declines significantly during the first year. Instantaneous value m is tied with production decline during 1 year by the formula m_y=1-exp(-m). The year decline in production during following years is not lower than 16% per year, which is significantly higher than in the production of conventional oil (4% in average).

If high decline rates remain the same, then production rates will lower in course of time and it makes it possible to consider production in the infinite interval of time without major errors. If we will take decline rate *m* as a constant value, we can use formula (1) for evaluation of recoverable reserves *V(t)* at the moment *t*

$$q(t) = q(12) \cdot e^{-m(t-12)}, \quad t \geq 12 \, , \tag{2}$$

where 30.4 – the average number of days in a month, *m* in [1/month].

As a result, the production decline rate m in model (1) will be in coincidence with the rate of recovery *m*.

3. Oil production model

Let's use an oil (gas) production model for a single well, based on two characteristics:

- residual recoverable reserves $V(t)$,
- production rate *m*.

These values depend on the field's properties, as well as on production technologies (well design and methods of reservoir stimulation).

We'll consider that instantaneous oil production rate *q(t)* of well in *t* moment of time

$$q(t) = -\frac{\mathrm{d}V}{\mathrm{d}t},$$

is proportional to residual reserves $V(t)$

$$q(t) = mV(t), \tag{3}$$

where recovery rate *m* is constant. Calculation of the obtained equation

$$\frac{\mathrm{d}V}{\mathrm{d}t} = -m \cdot V, \quad V(0) = V_1, \tag{4}$$

is written as

$$V(t) = V_1 \cdot e^{-m(t-t_0)}, \quad t \geq t_0, \tag{5}$$

where V_1 – initial recoverable reserves for a single well,
t_0 – the moment of production start at the well.

Then production rate $q(t)$ equals

$$q(t) = m \cdot V_1 \cdot e^{-m(t-t_0)},$$

production per time interval $[t_1, t_2]$, $t_1 \geq t_0$, $Q(t_1, t_2)$ equals

$$Q(t_1, t_2) = V(t_1) - V(t_2) = V_1 \cdot [e^{-m(t_1-t_0)} - e^{-m(t_2-t_0)}]. \tag{6}$$

4. Identification of the model

The Source of actual data for the model identification is the same plot as in [2].

Identification has its goal in finding values for V_1 and *m* parameters, and it makes it possible to move theoretical value $g_{\mathrm{th}}(i)$ as close to actual value $g_{\mathrm{f}}(i)$ on the plot as it possible. It will need function minimization

$$I = \sum_{i=1}^{ik} d_i \cdot \left(q_{\text{th}}(t) - q_{\text{f}}(t)\right)^2, \quad (7)$$

where i_k – the number of actual month in the chart.

Our end goal is to bring theoretical *NPV* for one shale well to forward to actual *NPV* values. It needs a close approximation of total discounted revenue. Therefore multipliers d_i were chosen as weight parameters in (7), these multipliers are used in the reduction of revenue to the initial moment.

It should be noted that instantaneous discount factor *E* is tied with the annual E_y factor by the function

$$E = \ln(1 + E_y).$$

We'll take in calculations E_y=10 % per year, then *E* =9.5 %.

Values of V_1 and *m* parameters, which are minimum for the (7) function, were found in the EXCEL software with the "Table" instrument. The most complete data is available for the 2012 year (78 months). For other years of putting wells into operation, there are data for 67, 55, 43, 31, 19 and 6 months. In order to have a possibility to match results of various years let's implement identification of the 2012 year model in accordance with the same time interval (Table 2).

For 6 and 19 months, there are good approximation qualities, for larger intervals it is bad. Nevertheless, reduction to (3) - (6) model has sense, cause for this model optimization task can be solved more easily.

A greater number of years in the interval results in a lower estimate of the recovery factor m and a greater estimate of recoverable reserves V_1 (Table 2).

Table 2 also shows total discounted production and adjustment factors which can help to transform *x*-months model into the model with *x* = 78.

Table 3 shows models identified by the first year.

Table 2. Parameters of approximations of the 2012 input data for the initial section.

Production rate at the end 2012 year, BOE/day	187	187	186	183	173	151	140	143
Production decline *m*, %/year	123	125	133	153	197	307	372	357
V(12), thous. BOE	1184	1169	1129	1039	894	699	629	649
Number of months	79	67	55	43	31	19	12	6
Adjustment factors								
for m	1	1	0.9	0.8	0.6	0.4	0.3	0.3
for V(0)	1	1	1	1.1	1.3	1.7	1.9	1.8
Accumulated discounted production, BOE	1541	1529	1504	1444	1341	1196	1138	1160

Table 3. First-year trend parameters.

Year of putting into operation	2012	2013	2014	2015	2016	2017	2018 (six points)
Production rate at the end of the year, BOE/day	140	116	143	176	288	294	303
Production decline m, % per year	372	468	535	475	340	382	450
Production decline my, per year, %	97.6	99	99.5	99.2	96.7	97.8	98.9
V (0) recoverable reserves, thous. BOE	629	513	631	780	1310	1320	1 348
V (12), thous. BOE	165	109	117	162	373	338	296

Table 4 shows models of the wells of the 2013 - 2018 years and their adjustment with the use of adjustment factors.

Table 4. Trend parameters for all actual data.

Year of putting into operation	2012	2013	2014	2015	2016	2017	2018
Production rate at the end of the year, BOE/day	187	176	227	255	374	333	304
Production decline m, %/year	123	74	108	151	145	284	450
After correction, %/year	123	73	100	121	91	114	155
V (0) recoverable reserves, thous. BOE	1184	1518	1541	1465	2180	1560	1348
After correction	1184	1538	1616	1669	2887	2642	2459
Number of months	79	67	55	43	31	19	6

5. Economical model

[2] has plots for the ratio of shale oil production $q_f(i)$ by months to the volume of injected proppant *P*, multiplied by the length of horizontal wellbores, i.e. the author considers $P \times L$ value as a good measure of action to the reservoir. Let's take those investments K_r into the reservoir stimulation are proportional to the degree of $P \cdot L$

$$K_r \sim (P \cdot L)^s .$$

We'll consider that *P*-value is proportional to recoverable reserves V_1 of the well with the use of selected technology. We'll consider that the initial production rate of the well $m \times V_1$ is proportional to the *L* value. As a result, we will have the formula for investments

$$K_r = b \cdot m^s \cdot V_1^{2s} , \tag{8}$$

where *b* – specific investments (values are not known).

For evaluation of $P \cdot L$ value, plots $\frac{q_f(i)}{P \cdot L}$ were digitized and dependencies between points on plots were calculated (Table 5).

Table 5. Average actual investments into the reservoir.

Year of putting into operation	2012	2013	2014	2015	2016	2017	2018
Multiplication P×L, MMlbs×Mft	45	58	74	75	97	118	143

Figure 2 shows the correspondence between $P{\cdot}L$ and $m{\cdot}V_1^2$.

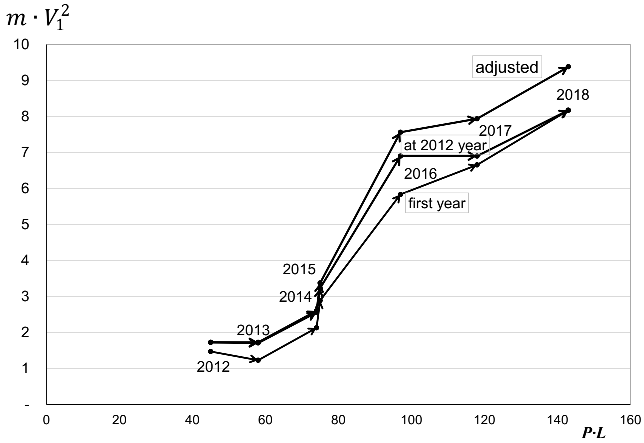

Figure 2. Dependence of $m{\cdot}V_1^2$ value on $P{\cdot}L$.

From year to year technology of the reservoir stimulation has been changing, production rates of wells have been increasing but investments have been growing as well.Let's draw a formula for *NPV*

$$NPV = \frac{(p-c)\cdot m \cdot V_1}{E+m} - K_V - b\cdot m^s \cdot V_1^{2s},$$

where p – product cost,
c – specific operating costs,
K_V – investments for drilling a vertical (inclined) well from the surface to the reservoir.

6. Necessary conditions for optimization

Let's write out the necessary conditions of the minimum NPV.

$$\frac{\partial NPV}{\partial m} = \frac{(p-c)EV_1}{(E+m)^2} - b\cdot s\cdot m^{s-1}\cdot V_1^{2s} = 0,$$

$$\frac{\partial NPV}{\partial V_1} = \frac{(p-c)\cdot m}{E+m} - 2b\cdot m^s \cdot s \cdot V_1^{2s-1} = 0.$$

We need to exclude bracket (*p-c*) from the system of two equations and to get a single equation, tying optimal values m and V_1. If oil's price p rises, then values of recovery rate m and recoverable reserves V_1 will rise. Far less grows wells' production rate. The volume of injected proppant P and horizontal wellbores length L grow too. But in case of price p decrease, it is necessary to return to a cheaper technology, i.e. to decrease P and L values.

7. Conclusions

In order to increase the cost efficiency of shale oil production it is necessary not to only optimize the initial production rate of the well, but recoverable reserves as well. Recoverable reserves can be identified with the use of the oil production decline plot.

The model should establish a link between the investment in the implementation of the technology and the production parameters. Intermediate parameters may be represented by horizontal wellbores' length and volume of injected proppant.

Production model refinement needs publication of actual data, natural and economic as well, including data on operational costs.

The establishment of an optimal correlation between production rate and recoverable reserves can be chosen as a goal, in other words: correlation between horizontal wellbores' length and injected proppant volume. The following step shall be the determination of the dependence of the best technologies on the price of oil.

8. References

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