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Production Optimization & Enhanced Oil Recovery (Introduction to New TOP™ Technology)

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Applicability and Key Benefits

The proposed innovative technology for Oil Production Optimization & Enhanced Oil Recovery (further in the text it's referred to as "TOP" – **T**echnology for **O**ptimization of **P**roduction) is primarily applied for **optimization of oil production from reservoirs containing oil with high Gas to Oil Ratio** (GOR>600 cft/bbl). It is used when bottomhole pressure is below bubble point pressure ($P_{\text{bottom}} < P_{\text{bubble pt}}$) and/or in case when a gas cone appears. TOP can be applied to all methods of oil production – flowing (fountain), gas lift, and pump production. However, it's most efficient for flowing and gas-lift wells.

The US Patent # 7,172,020, which was granted on Feb. 6, 2007, summarizes and protects all key aspects of TOP technology. Extension of this patent to Russia and other former SU countries is pending.

(12) **United States Patent**
Tseytlin

(10) **Patent No.:** **US 7,172,020 B2**
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(54) **OIL PRODUCTION OPTIMIZATION AND
ENHANCED RECOVERY METHOD AND
APPARATUS FOR OIL FIELDS WITH HIGH
GAS-TO-OIL RATIO**

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Primary Benefits of TOP:

- Increases the current Oil Production
- Increases the Ultimate Recovery Factor of the well and the oil field
- Reduces Gas (GOR) and Water (WOR) contents

Additional Benefits of TOP:

- Prolongs Life of Well
- Reduces (or eliminates) gas and water cones
- Decelerates depletion of formation pressure
- Improves stability of well performance
- Helps avoid premature loss of formation pressure and energy
- Eliminates appearance of high viscosity areas in formation near bottom hole zone
- Increases formation's relative permeability coefficient by oil
- Increases productivity index of the formation
- Increases efficiency of gas-lift and pumps
- Decreases electric energy consumed by pumps and gas-lift compressors
- Reduces formation sand washout, mechanical damages to the formation, and formation permeability loss

This technology is based on the solution of a set of **precise mathematical models (Simulator) of the entire system "reservoir-well" that accounts for all of its components.** This permits realization of a comprehensive analysis of processes that occur in the borehole, near-borehole zone, and in the formation. This, in turn, allows maximization of the current oil production rate and

enhancement of oil recovery due to keeping the current bottomhole pressure at the “optimal level”.

Principal novelty of TOP: maximum oil flow rate is reached at a certain value of downhole pressure between zero and the formation pressure. This value is called “Optimal Pressure”, or P_{opt} (Fig. 1), and it is precisely calculated by the Simulator. If bottomhole pressure falls below the bubble point pressure, in case of high GOR, relative permeability coefficient by oil decreases, because of gas saturation increase due to gas released from oil. Viscosity of de-gassed oil also increases. This leads to decrease in productivity index of formation, with this effect being stronger in affecting production rate than the increased depression. As a result, decreasing of bottomhole pressure below bubble point pressure can lead to decrease in production rate, but not to increase, as commonly used Vogel’s model predicts. Thus, as the bottomhole pressure decreases, at first the oil rate begins to increase due to increase of depression in formation. But starting from a specific bottomhole pressure value (called “optimal”) the oil output begins to decrease, even though the depression increases, which is opposed to predictions of widely known Vogel’s model. The reason for this is that after the optimal bottomhole pressure is achieved, influence of decreasing production index becomes dominating.

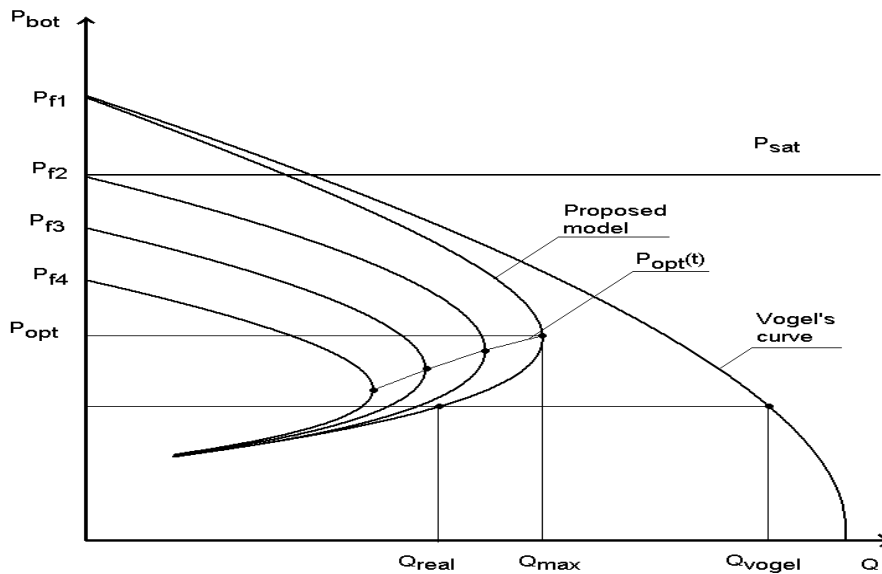


Fig. 1- Inflow Performance Relationship (IPR) curve

The fact that such an optimal pressure value exists has been proven both theoretically by running extensive modeling and practically by conducting several field experiments. This optimal pressure depends on formation parameters (permeability, porosity, saturation, and pressure), PVT characteristics of fluids ($R_s(P, T)$ – solution of gas in oil; $B_o(P, T)$ – oil formation volume factor; $B_g(P, T)$ – gas formation volume factor; $\mu_o(P, T)$ – oil viscosity; $\mu_g(P, T)$ – gas viscosity), and other characteristics of the entire system “Well – Reservoir”. Maximum oil rate is achieved by maintaining formation in the mode that minimizes negative effects in the bottomhole area (Fig.2). These detrimental effects appear due to the presence of a free gas separated from oil that blocks oil flow, as well as due to forming of zones of sluggish, viscous degassed oil. Utilization of this method also decelerates pressure drop in formation by lessening premature gassing from formation; it also decreases a current value of GOR. This leads to **extended life and increases ultimate oil recovery of a particular well.**

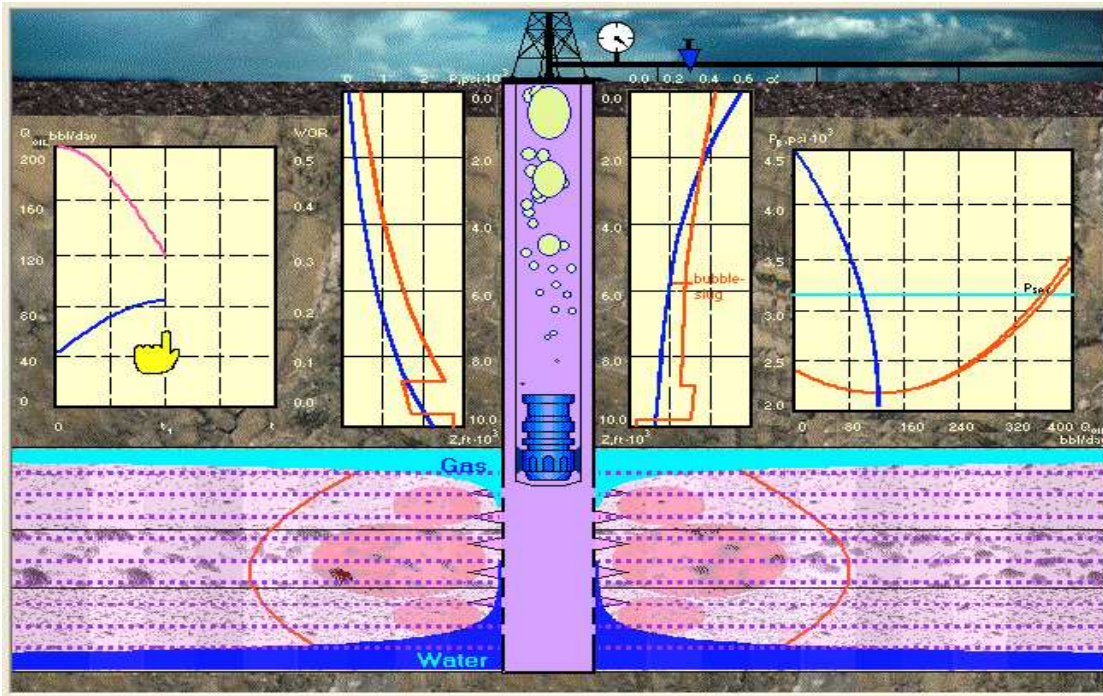


Fig.2 - Simulation of Negative Effects in Near-Bottomhole Zone

The proposed mathematical models allow **accurate calculation of optimal conditions for existing parameters of the formation and the system to reach maximum oil production.** In addition to determination of P_{opt} , these mathematical models and corresponding computer simulators allow determination of other parameters of the most optimal mode (e.g., optimal rate of injection, power of pumps, etc), calculation of critical design parameters of both surface and downhole tools (see below) used for implementation of this technology, and expected oil production improvement. Also, these high precision simulators allow diagnosis of current well conditions and prediction of its behavior in the future, including oil production rate, pressure, GOR, and the recovery index (example on Fig.3).

This technology can be relatively easily implemented by using a **Downhole Tool (DHT)** for adaptive regulation of downhole pressure during production. This tool automatically maintains this pressure at or close to the optimal level P_{opt} in various production conditions.

A number of wells suitable for potentially beneficial employment of TOP is really huge. TOP can be applied both during development of new oil fields and for improvement of older wells. The economic effect from implementation of this technology can be expressed in terms of getting **millions of additional barrels of oil or hundreds millions of dollars** without drilling extra wells or building additional expensive platforms for offshore production.

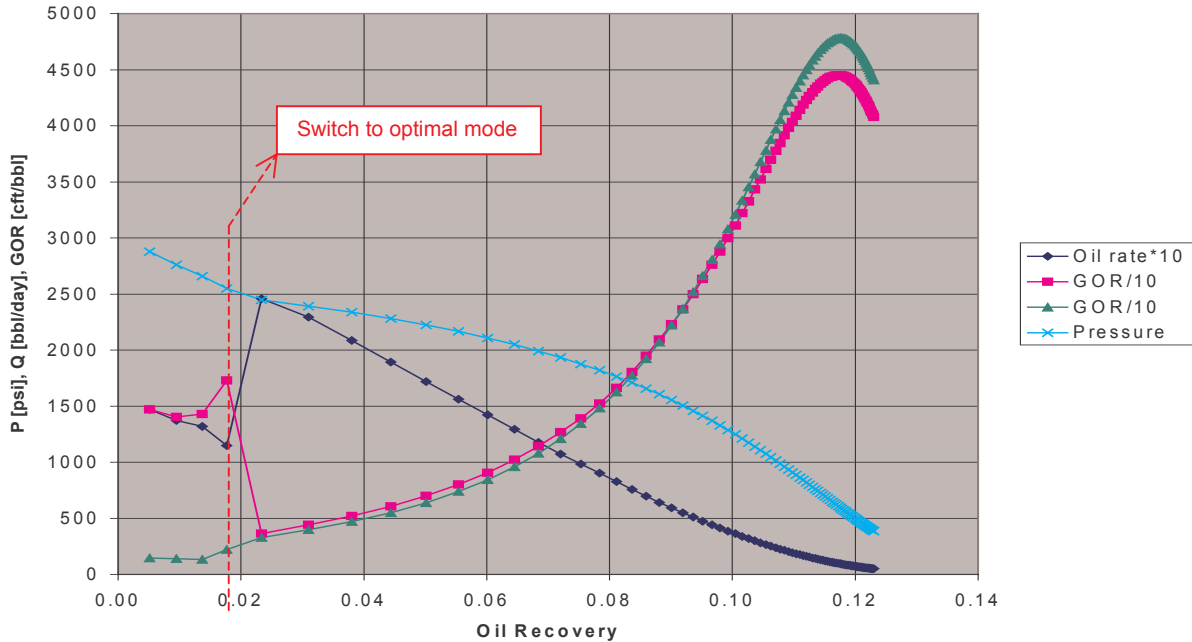


Fig.3 - Computer Simulation Results: Rate, Formation Pressure and GOR vs. Oil Recovery
 Initially this well was working in a non-optimal mode ($P_{bot} \neq P_{opt}$); then it was switched to an optimal mode when P_{bot} was maintained closely to the optimal value P_{opt}

Examples of Practical Utilization of TOP – Field Test Results

1) Well A1, South-East Asia (most recent field test, 2007-2008)

- Oil output increased from 148 to 318 bbl/day
- GOR reduced from 38440 cft/bbl to 12440 cft/bbl
- WOR reduced from 0.27 to 0.05
- Ultimate Oil Recovery will increase significantly because the well was stabilized and GOR and WOR are reduced
- Additional Oil received during two month period: 11,443 bbl (more than \$1,000,000 @ \$90/bbl)

2) Deep (13000 ft) offshore gas-lift well in Gulf of Mexico

- GOR decreased from 3282 to 1272 cft/bbl
- WOR decreased from 9.5 % to 0.43 % , i.e. the actual oil recovery increased
- After removal of TOP tool from the bottomhole assembly a sudden increase in oil flow rate was observed, since TOP helped to clean near borehole area within the perforation zone due to displacing the gas and water cones, reduced oil viscosity, and improving this zone permeability by oil, while reducing its permeability by gas.

3) Well 289 in Uzbekistan (Kokdumalak oil field)

- Use of TOP at Well 289 increased daily oil production 18%, up from 780 to 920 bpd, decreased GOR by 15% from 6000 to 4500 cft/bbl, and water cut to zero.
- Bottomhole TOP tool was installed in tubing for maintaining optimal bottomhole pressure and stabilizing well's performance.
- Skin effect was reduced in the bottomhole zone, and gas and water cones were eliminated within the perforation zone.
- The use of the TOP tool at Well 289 yielded approximately 37,500 additional barrels of oil over a nine-month period.

Oil Flowrate Qoil, GOR, and WOR vs. Time

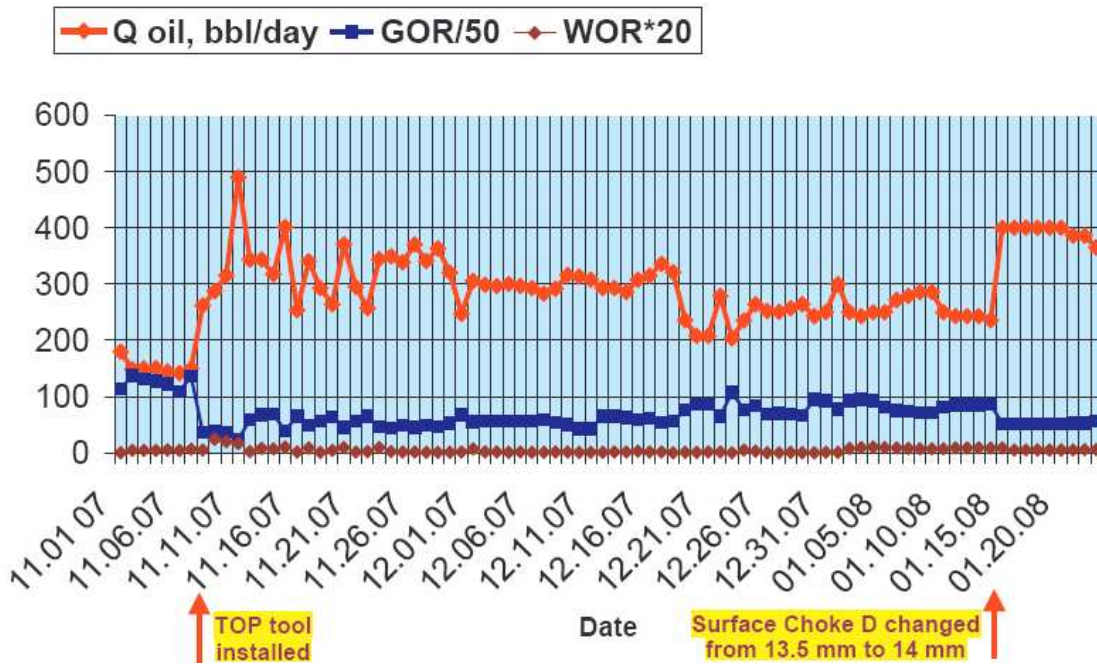


Fig. 4 – Results of most recent field test of TOP (Well A-1, South-East Asia)

Frequently Asked Questions on TOP:

Q1: What does the TOP Technology consist of?

TOP consists of the following key components that are bundled together to deliver a real-time solution to the Client:

- Firm Theoretical Background and Practical Proof of Existence of Inflow Performance Relationship curve (IPR) with Optimal Downhole Pressure not equal to zero
- Set of comprehensive Mathematical Models and Computer Simulators for simulating the Entire System “Surface Choke - Well - TOP Bottomhole Tool – Reservoir”
- TOP Bottomhole Tool for maintaining bottomhole pressure at Optimal Level
- Established Iterative Procedure for bringing the well to a desired state:



Actual Well Measurements -> Running Interactive Simulator -> -> Making Recommendations / Adjustments -> Next Iteration ...

Q2: Why can't we control the well from the surface, by using just a surface choke?

When GOR is high, a two-phase mixture with high gas content appears in the well tubing. A long column of gaseous fluid acts as a strong non-linear and delaying component and causes hysteresis in the control system. Propagation of the control signal is delayed by several dozens of seconds (speed of sound in aerated liquid is ~50-100 m/sec, i.e. lower than in liquid or gas). Because of this, effective control by adjusting bottomhole pressure becomes complicated. In result, the system "choke – well – formation" may develop positive feedback that destabilizes production mode, makes it difficult to maintain optimal bottomhole pressure, and the well can easily switch to a gas mode.

The utilization of a Bottomhole Control eliminates negative effects of such feedback. However, a simple bottomhole choke with hard regulation characteristic may not be sufficiently effective. To address this concern, we came up with a concept of a simple, but rather effective bottomhole tool that provides a stable producing mode due to introduced negative feedback that prevents a well from switching to a gas mode. However, the surface choke shall be used in conjunction with the TOP downhole tool to roughly set a working range of downhole pressure, as the TOP tool itself provides required fine-tuning of the pressure value to bring it to the optimal level, and it ensures selection of a stable working point on the IPR curve.

Q3: What are the specific practical steps for implementation of TOP in the field?

- **Step 1: Well Screening to determine whether TOP is suitable for a particular well**
 - Complete Questionnaire Form that is specially developed for TOP evaluation.
 - Run computer simulations based on provided information and well history.
 - Make final decision and provide recommendations on applicability of TOP for a proposed well.
- **Step 2:** If at Step 1 it's determined that a particular well is suitable for TOP, then determine potential benefits from implementation of TOP
 - Run computer simulations to forecast potential oil output increase and other expected benefits from implementation of TOP for a selected well
- **Step 3:** Select a specific tool design and calculate optimal parameters of TOP tool based on results of simulation at Steps 1 and 2
- **Step 4:** Build a chosen version of the TOP tool, install it in a mandrel, and deliver downhole by using a standard wireline procedure.
 - Certain adjustments of surface choke size and gas-lift valves may be also required based on simulation results
- **Step 5:** Close monitoring along with computer simulation of the producing well to bring it to the most optimal mode for a few days after installing TOP tool.
- **Step 6:** Exploitation of the well in the optimal production mode with periodic monitoring and verification of maintaining the optimal mode by running computer simulation, as needed.

Q4: Why does TOP enhance the ultimate oil recovery?

Application of TOP for wells with high GOR allows maintaining the pressure level downhole at the optimal level. This leads to optimization of both the current oil production (flow rate), as well as the oil production during the entire well life, while not allowing GOR and water content to rise. This, in turn, slows down the process of dropping the formation pressure. It results in a prolonged active producing life of the well.



At the same time, this slows down the effect of degassing (conversion of the gas dissolved in the oil to a free gas phase). Consequently, the processes of increasing the oil viscosity and, respectively, reducing oil's mobility in the reservoir slow down as well.

Besides, premature and excessive degassing of the gas dissolved in the oil reduces oil's volume and increases its density; this, in turn, reduces oil saturation and relative permeability in the reservoir.

Maintaining the downhole pressure at an optimal level stabilizes the well, increases an average oil production, and prevents switching the well into a gas mode.

All of the above leads to noticeable increase (in excess of 10%) of the ultimate oil-recovery factor for the reservoir.

Q5: How does TOP efficiency differ for different production methods?

TOP can be applied to any production method. However, due to some of TOP's specifics, its efficiency could vary for different methods.

The flowing (fountain) wells are the most suitable candidates for TOP, as all of these three factors shall be satisfied for fountain oil production.

On the second place – gas lift wells. Usually, they are characterized by a low formation pressure and/or low gas content, and/or high water content. However, often too much gas is pumped into a well, and it may cause forming a gas cone or appearance of a gas skin effect. Using TOP allows reduction of these adverse effects due to weakening of the positive feedback.

Pump production is the least suitable candidate for TOP. Pumps are usually used in the wells with low formation pressure or/and high water content. All types of pumps are not suitable for high gas content. Usually 15% is the highest value of the gas content (volume-based) suitable for pump production.

Sometimes, in special cases TOP can be efficiently used for pump production by conforming the pump performance to reservoir productivity. In this case, it is often not necessary to use a TOP downhole tool, as just a simple reduction of the pump efficiency can eliminate positive feedback that occurs due to inconformity. Please note that many production wells equipped with pumps work very inefficiently or switch to a gas production mode due to a false interpretation of the Vogel's IPR curve. It leads to keeping the bottomhole pressure at a very low level, and, as a result, to forming gas cones and appearance of a gas skin effect. Ultimately, this may prematurely "kill" the well.

In reality, just a comprehensive analysis of all parameters of a particular producing well allows proper evaluation of TOP efficiency for existing condition and production method.

For initial testing one should select a flowing (fountain) well that satisfies most of the selection criteria for TOP well candidates, as listed above. After that, the TOP methodology could be expanded with certain adjustments to pump wells, as well as to gas and gas-condensate wells.

Q6: Why hasn't this technology been broadly commercialized by now?

This Technology was under active development for the last 12-15 years and became mature just recently. Various aspects and the most critical components of this technology have been tested & tuned in the field over that period of time and demonstrated promising results. However, we did not want to broadly commercialize it until the key "know-how" items were fully understood, assessed, and reliably protected.

The US Patent # 7,172,020 that was granted and issued on Feb. 6, 2007 summarizes and protects all key aspects of this technology, including (but not limited to) theoretical findings, results of comprehensive modeling, and advanced downhole tool design. Extension of this patent to Russia and other former SU countries is pending.

In addition to this, the most critical components of this technology, such as design concept of the downhole tool and a suite of advanced computer models that accurately simulate behavior of the



entire system (“well – reservoir”) have been under continuous development and improvement during these years.

Simultaneously with this, the oil price significantly increased due to serious global concerns regarding energy supply shortage. New concepts of “intelligent wells” and similar technologies became of a great demand. This created an ideal background for introducing the proposed Technology on a commercial basis.

Appendix:

1. **US Patent # 7,172,020 (Feb. 6, 2007) on TOP technology**