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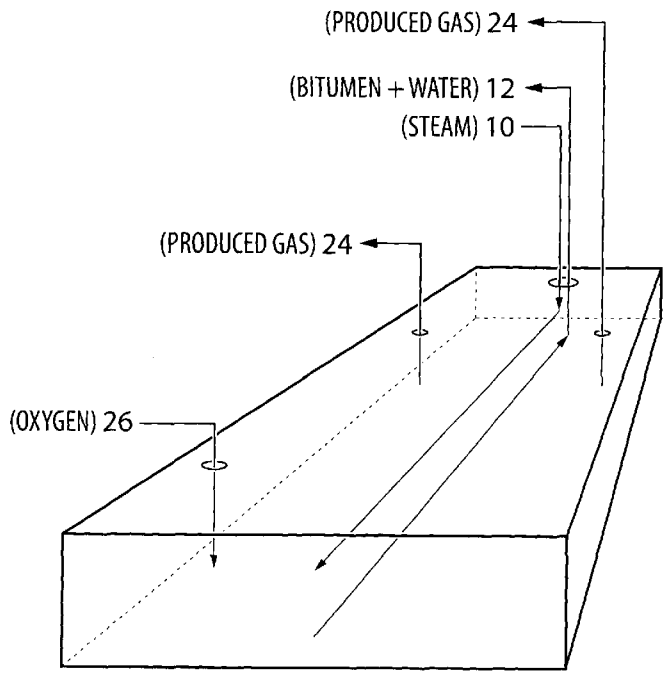
(54) Title: SAGDOX OPERATION IN LEAKY BITUMEN RESERVOIRS



SAGDOX

FIG.8

(57) Abstract: A method to operate a Steam Assisted Gravity Drainage with Oxygen (SAGDOX) process, in a leaky bitumen reservoir, wherein the process includes start-up, growth, decline and shut down phases. The start-up phase includes (1) Circulating steam in two horizontal (SAGD) wells, until communication is established between the two wells, (2) Injecting and optionally circulating steam in a SAGDOX oxygen injector well and vent gas well until communication is established, (3) Switching the wells to operate in a SAGD mode, with the upper well as a steam injector and the lower well as a fluid producer, creating a steam chamber, (4) Starting oxygen injection in the oxygen injector well, and (5) Opening at least one Produced Gas (PG) vent gas well, until steam injection is substantially limited to the upper well, oxygen injection has started and PG vent gas removal has started.

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TITLE OF THE INVENTION

SAGDOX Operation in Leaky Bitumen Reservoirs

FIELD OF THE INVENTION

Today's leading process to recover bitumen from Canada's Athabasca oil sands deposits is SAGD (Steam Assisted Gravity Drainage). SAGD is a saturated-steam process using two parallel horizontal wells. The upper well is a steam injector. The lower well is a fluid producer (bitumen + water). The process is operated by injecting steam to achieve a target pressure (pressure control) and to produce fluids at an average temperature (T) less than saturated steam T (sub-cool or steam-trap control).

Leaky reservoirs are bitumen reservoirs that produce an unusual amount of water using SAGD. Leaks may occur from top water, bottom water, or interspersed water lean zones (WLZ). SAGD performance may be seriously impaired in a leaky reservoir.

SAGDOX (Steam assisted gravity drainage with Oxygen) is an alternate process to SAGD that is a hybrid, combining SAGD and in situ combustion (ISC). SAGDOX has geometry similar to SAGD but adds two (or more) vertical wells to inject oxygen gas and to produce vent gas (combustion non-condensible gases). As well as the operational controls for SAGD (pressure control on steam injection and sub-cool control on production), SAGDOX adds oxygen injection and vent gas removal as control variables.

SAGD and SAGDOX EOR proceed through four distinct phases. In order, the phases are 1) start up, 2) growth, 3) decline, and 4) shut down. The transition from growth to decline occurs when the GD (gravity drainage) gas chamber reaches the net pay ceiling.

The process control objectives and methods are different for each stage of the SAGDOX process and are influenced by the characteristics of a leaky reservoir. This invention describes SAGDOX control methods for the SAGDOX stages in a leaky reservoir.

BACKGROUND OF THE INVENTION

The Athabasca bitumen resource in Alberta, Canada is unique for the following reasons:

(1) The resource, in Alberta, contains about 2.75 trillion bbls. of bitumen (Butler, R.M., "Thermal Recovery of Oil & Bitumen", Prentice Hall, 1991), including carbonate deposits. This is one of the world's largest liquid hydrocarbon resources. The recoverable resource, excluding carbonate deposits, is currently estimated as 170 billion bbls - 20% mining (34 billion bbls.) and 80% in-situ EOR (136 billion bbls) (CAPP, "The Facts on Oilsands", Nov. 2010). The in situ EOR estimate is based on SAGD, or a similar process.

(2) Conventional oil reservoirs have a top seal (cap rock) that prevents oil from leaking and contains the resource. Bitumen was formed by bacterial degradation of lighter source oil to a stage where the degraded bitumen is immobile under reservoir conditions. Bitumen reservoirs can be self-sealed (no cap rock seal). If an in situ EOR process hits the "ceiling", the process may not be contained and it can easily be contaminated by water or gas from above the bitumen.

(3) Bitumen density is close to the density of water or brine. Some bitumens are denser than water; some are less dense than water. During the bacterial-degradation and formation of bitumen, the hydrocarbon density can pass through a density transition and water can, at first, be less dense than the reservoir "oil". Bitumen reservoir water zones are found above the bitumen (top water), below the bitumen (bottom water), or interspersed in the bitumen net pay zone (water lean zones (WLZ)).

(4) Most bitumen was formed in a fluvial or estuary environment. Focusing on reservoir impairments, this has two consequences. First, there will be numerous reservoir inhomogeneities. Second, the scale of the inhomogeneities is likely to be less than the scale of a SAGD recovery pattern (Figure 1) or less than about 1000m in size. The expectation is that an "average" SAGD EOR process will encounter several inhomogeneities within each recovery pattern.

(5) The Athabasca bitumen reservoirs in Alberta, Canada are not always a "consolidated" reservoir (i.e. sandstone). Unconsolidated reservoirs can have different properties that are important. For example, the reservoir does not fracture as the pressure is increased. The equivalent term to fracture pressure is "parting" pressure. Also, sand in the steam-swept zone can become mobile under sufficient pressure gradients. Steam breakthrough to a production well can also carry sand and "sand blast" reservoir tubulars.

(6) Despite the unconsolidated nature of the reservoirs, the matrix permeability can be very high, particularly the vertical permeability. Permeabilities can be as high as about 6D. This is important for gravity drainage processes that rely on high vertical permeability for good drainage rates and high bitumen productivity.

Today's leading in situ EOR process to recover bitumen from Canada's oil sands is SAGD. SAGD is a bitumen EOR process that uses saturated steam to deliver energy to a bitumen reservoir. Figure 1 shows the basic SAGD geometry, using twin, parallel horizontal wells (up to about 1000m long) separated by about 5m spacing with the lower well parallel to the net pay basement, 2 to 8 m above the "floor". The upper well is in the same vertical plane and injects saturated steam into the reservoir. The steam heats the bitumen and the reservoir matrix. As the interface between steam and cold bitumen moves outward and upward it creates a gas, gravity-drainage chamber (Figure 2). The heated bitumen and condensed steam drain, by gravity, to the lower horizontal well that produces the liquids. The heated liquids (bitumen + water) are pumped (or conveyed) to the surface using ESP pumps or a gas-lift system.

Figure 2 shows how SAGD matures. A young steam chamber has bitumen drainage from steep sides and from the chamber ceiling. When the chamber grows and hits the top of the net pay zone, drainage from the chamber ceiling stops and the slope of the side walls decreases as the chamber continues to grow outward. For a good quality reservoir, bitumen productivity peaks at about 1000 bbls/d when the chamber hits the top of the net pay zone and falls as the chamber grows outward, until eventually the economic limit (10-20 years) is reached.

Since the produced fluids are at/near saturated steam temperatures, it is only the latent heat of the steam that contributes to the process in the reservoir. It is important to ensure that steam is high quality as it is injected into the reservoir.

A SAGD process in a good homogeneous reservoir can be characterized by only a few measurements:

(1) saturated steam T (or P)
(2) bitumen production rate (the key economic factor), and
(3) SOR – a measure of process efficiency

For an impaired reservoir, there is a fourth measurement, the water recycle ratio (WRR), to enable to see how much of our injected steam is returned as condensed water.

SAGD operation, in a good-quality reservoir, is straightforward. Steam injection rate, into the upper horizontal well, and steam pressure are controlled by pressure targets chosen by the operator. If the pressure is below the target, steam pressure and injection rates are increased. The opposite is done if pressure is above the target. Production rates from the lower horizontal well are controlled to achieve sub-cool targets in the average temperature of the production fluids. The sub-cool is the difference in temperature of saturated steam and the actual temperature of produced liquids (bitumen + water). Produced fluids are kept at lower T than saturated steam to ensure that live steam does not get produced. 20°C is a typical sub-cool target. This is also called steam trap control.

The SAGD operator has two choices to make—the sub-cool target and the operating pressure of the process. Sub-cool is safety issue, but operating pressure is more subtle and usually more important. The higher the pressure, the higher the temperature—linked by the properties of saturated steam (Figure 3). As operating temperature rises, so does the

temperature of the heated bitumen which, in turn, reduces bitumen viscosity. Bitumen viscosity is a strong function of temperature (Figure 4). The productivity of a SAGD well pair is proportional to the square root of the inverse bitumen viscosity (Butler (1991)). So the higher the pressure, the faster bitumen can be recovered - a key economic performance factor.

But, efficiency is lost if pressures are increased. It is only the latent heat of steam that contributes (in the reservoir) to SAGD. As steam P and T are increased to improve productivity, the latent heat content of steam drops (Figure 3). In addition, as P and T are increased, more energy is needed to heat the reservoir matrix up to saturated steam's T and heat losses increase.

The SAGD operator usually opts to maximize economic returns, so the operator increases P and T as much as possible. Pressures are usually much greater than native reservoir P. A few operators have gone too far and exceeded parting pressure (fracture pressure) and caused a surface breakthrough of steam and sand (Roche, P., "Beyond Steam", New Tech. Mag., Sept 2011).

There also may be a hydraulic limit for SAGD (Figure 5). The hydrostatic head between the two SAGD wells is about 8 psia (56 kPa). When pumping or producing bitumen and water, there is a "natural" pressure drop in the well due to frictional forces. If this pressure drop exceeds the hydrostatic head, the steam/liquid interface can be "tilted", and it can intersect the producer or injector well (Figure 5). If the producer well is intersected, steam can break through. If the injector well is intersected, it can be flooded and effective injector length can be shortened. For current, standard pipe sizes and a 5m spacing between wells, SAGD well lengths are limited to about 1000m due to this limitation.

One of the common remedies for an impaired SAGD reservoir, that has water incursion, is to lower the SAGD operating pressure to "match" native reservoir pressure—also called low-pressure SAGD. But this at best is difficult and at worst impractical for the following reasons:

(1) There is a natural hydrostatic pressure gradient in the net pay region. For example for 30m of net pay, the hydrostatic head is about 50 psi (335kPa). Because the steam chamber is a gas, it is at constant pressure. What operating pressure is chosen to match reservoir P?

(2) There are also lateral pressure gradients in SAGD. The pipe size for the SAGD producer is chosen so that the natural pressure gradient, when pumping, is less than the hydrostatic pressure difference between SAGD steam injector and bitumen producer (about 8 psi or 56 kPa). How can SAGD P match to the reservoir P if there is a lateral pressure gradient?

(3) Pressure control for SAGD is difficult and measurements are inexact. A pressure control uncertainty of ± 200 kPa is to be expected.

Zones with high water saturation are known as WLZ. WLZ can be at the top of the bitumen reservoir (top water), at the bottom (bottom water), or interspersed within the pay zone.

Interspersed Bitumen WLZ is best seen in Figure 6. The following may be said about this type of zone:

i. Interspersed WLZ have to be heated so that GD steam chambers can envelop the zone and continue growth of the GD chamber above and around the WLZ blockage.

ii. A WLZ has a higher heat capacity than a bitumen pay zone. Table 3 shows a 25% Cp increase for a WLZ compared to a pay zone.

iii. A WLZ also has higher heat conductivity than a bitumen pay zone. For the example in (2), WLZ has more than double the heat conductivity of the bitumen pay zone.

iv. So, even if the WLZ is not recharged by an aquifer or bottom/top water, the WLZ will incur a thermal penalty as the steam chamber moves through it. Also, since the WLZ has little bitumen, bitumen productivity will also suffer as the steam zone moves through a WLZ.

v. SAGD steam can heat WLZ water to/near saturated steam T, but it cannot vaporize WLZ water. Breaching of the WLZ, will require water to drain as a liquid.

vi. If the interspersed WLZ acts as a thief zone, the problems are most severe. The WLZ can channel steam away from the SAGD steam chamber. If the steam condenses prior to removal, the water is lost but the heat can be retained. But, if the steam exits the GD steam chamber prior to condensing, both the heat and the water are lost to the process.

vii. The obvious remedy is to reduce SAGD pressures to minimize the outflow of steam or water. But, if this is done, bitumen productivity will be reduced.

viii. If pressures are reduced too far or if local pressures are too low, cold water from a WLZ thief zone can flow into the steam GD chamber or toward the SAGD production well. If this occurs, water production can exceed steam injection. More importantly, for a large water inflow, steam trap control (sub-cool control) is lost as a method to control SAGD.

ix. Interspersed WLZ's can distort SAGD steam chamber shapes, particularly if the WLZ is limited in lateral size. Normal growth is slowed down as the WLZ is breached. This can reduce productivity, decrease efficiency, and limit recovery.

With respect to bottom water zones, as best seen in Figure 7, the issues are similar to interspersed WLZ except that 1) bottom water underlies the bitumen and 2) the usual expectation is that bottom water is more active. SAGD can operate at pressures greater than reservoir pressure as long as the following occurs: 1) pressure drops in the production well (due to flow/pumping) do not reduce local pressures below reservoir P and 2) the bottom of the reservoir, underneath the production well, is "sealed" by high-viscosity immobile bitumen (basement bitumen). As the process matures, basement bitumen will become heated by conduction from the production well. After a few years, this bitumen will become partially mobile and SAGD pressure will need to be reduced to match reservoir pressure. This can be a delicate balance. SAGD pressures cannot be too high or a channel may form, (reverse cone) allowing communication with the bottom water. SAGD steam pressures cannot be too low either or water will be drawn from the bottom water (cresting). If this occurs, water production will exceed steam injection.

The higher the pressure drops in the production well, the more delicate the balance and the more difficult it is to achieve a balance.

If the reservoir is inhomogeneous or if the heating pattern is inhomogeneous, the channel or crests can be partial and the onset of the problem is accelerated.

With respect to top water zones, as best seen in Figure 7, again, the issues are similar to interspersed WLZ and bottom water, with the expectation that top water is also an active water supply. The problems are similar to bottom water, as above, except that SAGD wells are further away from top water. So, the initial period–when the process can be operated at higher pressures than reservoir pressure–can be extended compared to bottom water. The pressure drop in the production well is less of a concern because it is far away from the ceiling. The first problem is likely to be steam breaching the top water interface. If the top water is active, water will flood the chamber and may shut the SAGD process down.

i. Industry experience with WLZ may be summarized as follows: Suncor's Firebag SAGD project and Nexen's Long Lake project each have reported interspersed WLZ that can behave as thief zones when SAGD pressures are too high, forcing the operators to choose SAGD pressures that are lower than desirable (Triangle Three Engineering, "Technical Audit report, Gas Over Bitumen Technical Solutions", Dec.2010)

ii. Water encroachment from bottom water for SAGD can also cause more well workovers (i.e. downtime) because of unbalanced steam and lift issues (Jorshari, K. "Technology Summary", JCPT, Mar.2011).

iii. Simulation studies of a particular reservoir concluded that a 3m standoff (3m from the SAGD producer to the bitumen/water interface) was sufficient

to optimize production with bottom water, allowing a 1m control for drilling accuracy (Akram, F. 'Reservoir Simulation Optimizes SAGD', American O&G Reporter, Sept.2010). Allowing for coring/seismic control, the standoff may be higher.

iv. Nexen and OPTI have reported that interspersed WLZ seriously impedes SAGD bitumen productivity and increase SOR beyond original expectations at Long Lake, Alberta (Vanderklippe, N. "Long Lake Project hits Sticky Patch", Globe & Mail, Feb. 10, 2011), (Bouchard, J. et al., "Scratching below the Surface Issues at Long Lake – Part 2",Raymond James, Feb. 11, 2011), (Nexen Inc. "Second Quarter Results", press release, Aug.4, 2011), (Haggett, J et al., "Update 3-Long Lake oilsands output may lag targets", Reuters, Feb. 10, 2011).

v. Long Lake lean zones have been reported to make up from less than 3 to 5% (v/v) of the reservoir (Vanderklippe (2011)), Nexen Inc (2011)).

vi. Oilsands Quest reported a bitumen reservoir with top lean zones that are "thin to moderate". Some areas had a "continuous top thick lean zones" (Oilsands Quest, "Management Presentation", Jan. 2011).

vii. Johnson reported Connacher's oil sand project with a top bitumen water lean zone. The lean zone was reported to differ from an aquifer in two ways— "the lean zone is not charged and it limited size" (Johnson, M.D. et al., "Production Optimization at Connacher's Pod One (Great Divide) Oil Sands Project", SPE 145091-MS, 2011).

viii. Thimm reported on Shell's Peace River Project, including a "basal lean bitumen zone". The statistical analysis of the steam soak process (CSS) showed performance correlated with the geology of the lean zone (i.e. the lean zone quality was the important factor). The process chosen took advantage of WLZ properties, particularly the good steam injectivity in

WLZ's (Thimm, H.F. et al., "A Statistical Analysis of the Early Peace River Thermal Project Performance", JCPT, Jan., 1993).

ix. A cold water injectivity test is a way to potentially detect connections between SAGD wells and WLZ, top water and/or bottom water (Aherne, A.L. et al., "Fluid Movement in the SAGD Process: A Review of the Dover Project", Can. Int'l Pet. Conf., June 13, 2006).

SAGDOX is a process similar to SAGD; however, it uses oxygen gas as well as steam to provide energy to the reservoir to heat bitumen. The GD chamber is preserved, but it contains a mixture of steam and hot combustion gases.

SAGDOX can be considered a hybrid process, combining steam EOR (SAGD) and in situ combustion (ISC). SAGDOX preserves the SAGD horizontal well pair, but the process adds at least two new wells (Figure 8) – one well to inject oxygen gas and a second well to remove non-condensable combustion gases. Compared to SAGD, SAGDOX has the following advantages/features:

1. Steam adds heat directly by condensing; Oxygen adds heat by combusting residual bitumen.
2. Per unit heat delivered to the reservoir, oxygen is significantly less costly than steam.
3. Per unit heat delivered to the reservoir the volume of oxygen needed is about one-tenth the volume of steam (Table 1), so gas volumes of steam and oxygen mixes can be much less than for steam only.
4. Steam-only processes use saturated steam in the reservoir, so T and P conditions are limited by the properties of saturated steam (Figure 3). If pressure needs to be reduced to approach native reservoir P, temperatures will be reduced automatically. Oxygen mixtures of O_2 and steam can remove this constraint.

Combustion temperatures are higher than saturated steam P (~600°C vs. 200°C), and they are not tied to reservoir P.

5. Steam helps combustion: it preheats the reservoir so ignition can be spontaneous; it add OH and H radicals to the combustion zone to improve and stabilize combustion; and it acts as a heat transfer medium by condensing at the cold hydrocarbon interface to release latent heat.
6. Oxygen helps steam: combustion produces steam as a chemical product of combustion; connate water is vaporized; and water can be refluxed. Most importantly, at the same reservoir P, combustion can operate at a higher average T than steam.
7. The oxygen content in steam and oxygen mixes (e.g. Table 1) is used as a way to label the process. The term mix or mixture doesn't imply that a mixture is injected, or that good mixing is a prerequisite for the EOR process. It is only a convenient way to label the process. In fact, the preferred process has separate injectors for oxygen and steam.
8. There is a preferred range of O_2 content in steam + oxygen mixtures (from about 5 to 50% (v/v)). Below 5% oxygen, the combustion zone is very small and, if mixed, combustion can start to become unstable. Above 50% oxygen, steam levels in the reservoir can become too low for good heat transfer and produced liquids (water + bitumen) are too rich in bitumen for good flow.

SAGDOX also has the following features that can be helpful for EOR in impaired bitumen reservoirs:

1. The vertical oxygen injector vertical wells and the produced gas (PG) vent wells are small diameter wells - 3 to 4 inches for most SAGDOX operations. The wells are inexpensive to drill.
2. Multiple O_2 injectors and PG vents do not detract from SAGDOX performance. In fact, multiple wells help in conformance control.
3. If multiple oxygen injectors or PG vent wells are needed, the individual well diameters are in the 2 to 3 inch range. These wells can potentially be drilled using coiled tubing rigs.

4. The oxygen injector can be completed in/near a WLZ (water lean zone) or near a shale barrier to take advantage of residual fuel in the WLZ or hydrocarbon fuel in shales.
5. Especially at lower pressures (< 2000 kpa), SAGDOX can have average T much higher than SAGD. Combustion occurs at T between 400 and 800°C (HTO), compared to steam T < 250°C.
6. SAGDOX higher T's can aid in vaporization of WLZ water.
7. For the same bitumen production rates, SAGDOX has lower fluid flow rates (bitumen + water) in the horizontal production well. This will lower pressure drops down the length of the well, producing a more-even pressure distribution than SAGD.
8. Energy costs for steam + oxygen mixes are less than steam. Compared to SAGD, a SAGDOX recovery process can be run out longer to increase reserves and thinner pays can be developed.

There is a need to improve SAGDOX operations in a leaky reservoir, and in particular control operating parameters in SAGDOX operations in a leaky reservoir.

SUMMARY OF THE INVENTION

The following acronyms will be used herein.

AOGR	American Oil & Gas Reporter
CAPP	Canadian Association of Petroleum Producers
CMG	Computer Modeling Group
D	Permeability, Darcies
EOR	Enhanced Oil Recovery
ESP	Electric Submersible Pumps
ETOR	Energy to Oil Ratio (MMBTU/bbl)
GD	Gravity Drainage
HTO	High T Oxidation
ISC	In Situ Combustion
JCPT	Journal Canadian Petroleum Technology
LTO	Low T Oxidation
P	Pressure
PG	Produced Gas (combustion gas)

SAGD	Steam Assisted Gravity Drainage
SAGDOX	SAGD with Oxygen
SOR	Steam to Oil Ratio (v/v)
SPE	Society of Petroleum Engineers
T	Temperature
(v/v)	Volume/Volume
WLZ	Water Lean Zones
WRR	Water Recycle Ratio (v/v)

According to one aspect of the invention, there is provided a method to operate a SAGDOX process, in a leaky bitumen reservoir, wherein said SAGDOX process comprises a start-up phase, growth phase, decline phase and shut down phase, said method comprising, at the start-up phase:

(1) Circulating steam in two horizontal SAGD wells, until communication is established between said two horizontal SAGD wells,
(2) Injecting and optionally circulating steam in a SAGDOX oxygen injector well and vent gas well until communication is established,
(3) Switching the horizontal wells to operate in a SAGD mode, with the upper well as a steam injector and the lower well as a fluid producer, creating a steam chamber,
(4) Starting oxygen injection in the SAGDOX oxygen injector well, with O_2/steam (v/v) ratios of from about 0.05 to about 0.15,
(5) Opening at least one PG vent gas well, preferably to allow combustion gases to escape and to help control pressure and WRR, until steam injection is substantially limited to the upper horizontal well, oxygen injection has started and PG vent gas removal has started.

According to another aspect of the invention, there is provided a method to operate a SAGDOX process, in a leaky bitumen reservoir, wherein said SAGDOX process comprises a start-up phase, growth phase, decline phase and shut down phase, in the growth phase of the process, preferably to increase/optimize bitumen productivity and preferably to achieve a WRR target for the process, said method comprising:

(1) Adjusting oxygen/steam ratios (v/v),
(2) Adjusting energy injection rates (steam + oxygen) by controlling volumes and ratios,
(3) Adjusting vent gas well rates,
(4) Adjusting production well sub-cool targets, until bitumen productivity peaks.

In one embodiment, the end of the growth phase is achieved at the peak of bitumen productivity.

According to another aspect of the invention, there is provided a method to operate a SAGDOX process, in a leaky bitumen reservoir, wherein said SAGDOX process comprises a start-up phase, growth phase, decline phase and shut down phase, in the decline phase of the process, preferably resulting in at least one of improving energy efficiency, reducing costs, maximizing bitumen recovery and achieving a WRR target, comprising:

(1) Increasing the oxygen/steam (v/v) ratio, preferably to a maximum of 1.0,
(2) Adjusting PG vent gas rates,
(3) Adjusting energy injection rates (steam + oxygen) by controlling volumes and ratios,
(4) Adjusting production well sub-cool targets, preferably until economic limit for the SAGDOX process is substantially achieved.

According to another aspect of the invention, there is provided a method to operate a SAGDOX process in a leaky bitumen reservoir, wherein said SAGDOX process comprises a start-up phase, growth phase, decline phase and shut down phase in the shut-down phase of the process, preferably maximizing economic bitumen recovery, comprising:

(1) Shutting off steam injection,
(2) Adjusting oxygen injection rates,

(3) shutting off oxygen injection upon substantially achieving final economic limit, and

(4) Continuing residual bitumen production until the final economic limit is substantially achieved.

In one embodiment, said SAGDOX process has system pressures less than reservoir parting pressure.

In another embodiment, said SAGDOX process has system pressures greater than, or substantially equal to, native reservoir pressure.

In another preferred embodiment, said vent gas removal in said SAGDOX process is subject to the following constraints:

(1) The dry gas composition of the vent gas contains less than 5% (v/v) oxygen,

(2) The wet gas composition of the vent gas (at surface) contains less than 20% (v/v) steam, and

(3) The cumulative vent gas volume (dry, hydrocarbon-free basis) is less than the cumulative oxygen gas injected.

Preferably, in the SAGDOX process pressure targets are replaced by WRR targets.

Preferably, in the SAGDOX process, the WRR target is between 0.5 and 1.2, more preferably between 0.8 and 1.2, and most preferably between 0.9 and 1.2.

Preferably the SAGDOX process has a sub cool target between 5°C and 30°C.

The SAGDOX process further comprises adjusting combustion conformance by adjusting individual PG vent well rates.

In one embodiment of the invention, wherein the leaky bitumen reservoir comprises a top water zone, said process further comprises adjusting PG vent well production, creating a

top zone from non-condensable gases, acting as an insulator and thus minimizing GD chamber vertical growth and maximizing horizontal growth.

In another embodiment, efficiency of the process is monitored by ETOR.

Preferably said bitumen is a liquid hydrocarbon with API < 10 and viscosity > 100,000 cp.

In another embodiment said leaky bitumen reservoir has a WRR outside the range 0.9 to 1.1, after 200 days or more of SAGDOX operation.

Preferably the bitumen reservoir is determined to be leaky by a cold water injection testing, preferably performed prior to start-up.

In another embodiment the bitumen reservoir is determined to be leaky based on geological or geophysical data/interpretation prior to start-up.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 depicts a typical SAGD well configuration
Figure 2 depicts the stages in a SAGD operation
Figure 3 depicts Saturated Steam Properties
Figure 4 depicts Bitumen and heavy Oil Viscosities versus Temperature
Figure 5 depicts SAGD Hydraulic Limits
Figure 6 depicts Interspersed Bitumen Lean Zones
Figure 7 depicts Top and bottom Water Zones
Figure 8 depicts a SAGDOX well configuration
Figure 9 depicts a SAGD Simulation
Figure 10 depicts Case 1
Figure 11 depicts Case 2
Figure 12 depicts Case 2(a)
Figure 13 depicts Case 3
Figure 14 depicts Case 4
Figure 15 depicts Case 5
Figure 16 depicts Cumulative Performances of Cases 1 through 3
Figure 17 depicts Cumulative Performances of Cases 1, 4 and 5
Figure 18 depicts Dual Well Pair Production and Performance of Case 1 and 2

Figure 19 depicts Pressure Control Performance of Connected Well Pairs of Case 1 and 2
Figure 20 depicts the WRR performance with crossflow in connected well pairs of Case 3
Figure 21 depicts the WRR performance of connected well pairs of Cases 1 and 3
Figure 22 depicts the SOR Performance of Case 1 and 3
Figure 23 depicts Individual Well Pair Bitumen Production of Case 3
Figure 24 depicts Well Pair Bitumen Production Rates of Case 1 and 3
Figure 25 depicts the WRR Performance for a Homogeneous Reservoir with Contained SAGD
Figure 26 depicts Steam volumes occupying Bitumen voidages and the SOR
Figure 27 depicts a Schematic of a well Pair Cross-flow Model
Figure 28 depicts Water lean zone Bitumen recovery

DETAILED DESCRIPTION OF THE INVENTION

The subject of this invention is SAGDOX operations in a "leaky" bitumen reservoir. First, one needs to define what is considered a leaky reservoir using simulations of SAGD as an example. Then, one needs to consider how SAGDOX may be effectively operated in such reservoirs, for the four phases of operation for SAGD or SAGDOX processes (see Figure 2) – namely:

(1) Start-up
(2) Growth - when the GD chamber is growing vertically and laterally. Bitumen production is sourced from ceiling drainage and lateral drainage from steep GD wells.
(3) Decline - after the GD chamber hits the ceiling and vertical growth is halted. Bitumen production has limited ceiling drainage and the slope of the lateral walls declines.
(4) Shut Down - Bitumen production reaches its economic limit for SAGDOX (SAGD)

Example 1 - SAGD Simulations

Simulation of SAGD with the assumptions shown in Table 4 was studied. Sensitivities were studied for a homogeneous contained reservoir, dual well pairs connected by a WLZ

at constant pressure, dual well pairs with a WLZ at a ΔP= 300 kpa, the effect of dropping pressure control and using volume control after 1 year, and the effect of a thinner WLZ.

Figure 9 shows the predicted performance of the homogeneous contains (no leaks) reservoir. Figures 10 to 24 show the performance of dual well pairs connected by a WLZ for the various sensitivities studied (leaky reservoir). Figures 20, 21, and 25 show how the WRR varied for the simulations. WRR is the volume ratio of water produced to steam injected, both measured as condensed water. WRR is a measurement that can indicate whether or not water is leaking into or out from a SAGD pattern volume.

In this instance, a "leaky" pattern is one that produces an unusual amount of water in a bitumen reservoir (i.e. a leaky bitumen reservoir). The pattern may have water leaks in/out of the pattern volume to other portions of the reservoir; it can have water leaks to/from an adjacent reservoir pattern; or, it can produce unusual water volumes from WLZ within the reservoir. In order to further define "leakiness," the WRR will be used as an indicator (the volume ratio of produced water to steam injected, where steam is measured as a water-volume equivalent)

For a homogeneous reservoir, without fluid leaks and without WLZ in the pay zone, Figure 25 shows the expected WRR behaviour. In the early SAGD stages (100-300 days), WRR is between 0.90-0.95. For this period, the GD steam chamber is forming and the GD area is heating up. An inventory of liquid water is created in the reservoir. As the SAGD process continues, WRR increases gradually from about 0.96 to 0.99. If the bitumen voidage is occupied by steam only, one would expect WRR to be greater than 0.99 (Figure 11). For the later stages of SAGD, bitumen production (and voidage) is small and the WRR approaches the 0.99 value (Figure 25). A reasonable target for WRR for a perfectly contained SAGD GD chamber and a homogeneous reservoir during the peak period of SAGD (500-1500 days) is about 0.97.

Using the simulation results, there are three ways to define what a "leaky" bitumen reservoir is:

(1) If WRR deviates from 1.0 by more than ±0.10 after 200 or more days of continuous operation using pressure control, the reservoir can be deemed as "leaky". Using this definition the Case 3 simulation, WRR performance in Figure 23 would result in both well pair patterns deemed as "leaky". Well pairs 1 and 2 both deviate from the target by more than ± 0.10.

(2) If prior geological knowledge places WLZ, top water, or bottom water in or adjacent to the pattern (Figures 6 and 7), the pattern may be designated as "leaky" or potentially "leaky".

(3) If a cold water injection test is conducted prior to starting the EOR process and if the test indicated significant injectivity (Aherne (2006)), the pattern can be designated as "leaky" or potentially "leaky".

SAGDOX Operational Measurements and Control Variables

SAGD typically has measurements of the following:

(1) Downhole T, P

(2) Produced fluid (bitumen + water) T and flow rates

(3) Produced fluid water/oil cuts

(4) Steam injection rates

SAGD operators typically calculate the following parameters that can be used for process characterization and control:

(1) SOR (steam to oil (v/v) ratio), with steam measured as its condensed water equivalent

(2) Bitumen production rate

(3) Water production rate

(4) Sub cool equals the difference between saturated steam T in the reservoir (near the production well) and produced fluid T.

SAGDOX includes all the measurements and parameters as with SAGD, but with the following suggested additions:

(1) Dissolved gas in produced fluids
(2) Oxygen injection rates, oxygen composition and T, P
(3) Produced gas (PG) (vent gas) rates, gas composition, and T, P.
(4) ETOR (energy to oil ratio) assumed net energy injection rates for oxygen at 480 BTU/SCF (Butler (1991)) and for steam at 1000BTU/lb.
(5) WRR (the water recycle ratio)
(6) The oxygen/steam ratio (v/v)
(7) The PG/oxygen ratio (v/v)
(8) Calculating an oxygen balance to ensure HTO is active.

Another comparison that may be important is defining the control variables. For SAGD the answer is the steam injection rate and the fluid (bitumen + water) production rates.

For SAGDOX the operator has much more flexibility, with the same controls as SAGD but with the following extra controls:

(1) The oxygen injection rate
(2) The PG (vent gas) removal rate
(3) If multiple wells for SAGDOX are used, one can also control the oxygen and PG distribution within the reservoir.

Example 2 - SAGDOX Control in a Non-Leaky Reservoir

A non-leaky bitumen reservoir is one that has no substantial water leaks, independent of process operating pressure. Non-leaky reservoirs are not necessarily homogeneous. They may contain shales and other non-leaky impairments. SAGDOX operation in non-leaky bitumen reservoirs has the following elements.

(1) Start-up – the early objective in this phase is to start-up the two horizontal wells in the SAGD mode and to form a GD steam chamber. This objective is

accomplished, similar to SAGD, by circulating steam in each of the horizontal wells until the wells communicate. Steam circulation pressures cannot exceed reservoir parting pressure. After communication is established, the lower horizontal well is converted to a fluid producer, and the upper well is converted to a steam injector. In a conventional SAGD process, this procedure can take from about 3 to 6 months.

For SAGDOX, at the same time, a secondary objective is to connect the oxygen injection well and the PG vent wells (Figure 8) with the steam chamber and/or with the horizontal wells, so a transition to SAGDOX can be effected as early as possible. There is some urgency to the transition because SAGDOX energy costs are much less than SAGD energy costs. The objective is accomplished by circulating steam in each of the oxygen injector and PG vent wells. When it is determined that all wells are in communications, oxygen injection is started, preferable at low oxygen/steam ratios (0.05 to 0.15(v/v)) for safety reasons. The ratio can then be adjusted upwards to achieve target ratios. PG vent gas wells are opened to allow vent gas production and to control GD chamber pressures, subject to the following constraints:

(i) Pressures should not exceed reservoir parting pressures.

(ii) The dry gas composition of the PG vent gas should not contain more than 5.0% (v/v) of oxygen, preferably the PG vent gas should not contain more than 1.0% (v/v) of oxygen.

(iii) The PG vent gas cumulative volume of dry gas should not exceed the cumulative volume of oxygen injected.

(iv) The gas composition of the PG vent gas should not contain more than about 20% (v/v) of steam.

PG vent well constraints can be attained by adjusting PG vent volumes, adjusting volume ratios for more than one PG vent well or by adjusting oxygen injection rates.

(2) Growth – as SAGDOX continues to operate, the GD gas chamber (containing steam and some combustion gases) grows upwards toward the pay ceiling and outwards at the chamber walls. Bitumen drainage occurs at the ceiling and down the chamber walls. Bitumen productivity increases until the GD gas chamber hits the pay ceiling (Figure 2) - the end of the growth phase. The prime objective during this phase is to maximize bitumen productivity, while achieving a good ETOR. Similar constraints are applied to PG vent wells as during the start-up phase. The extra objective is attained by:

(i) Adjusting oxygen/steam ratios
(ii) Adjusting (increasing) energy injection rates
(iii) Adjusting (increasing) pressure targets
(iv) Adjusting sub-cool targets for the horizontal production well
(v) Adjusting/improving conformance of oxygen/combustion by altering flows to PG vent wells.

(3) Decline – after the GD gas chamber has hit the top of the pay zone, the SAGDOX recovery process loses productivity because bitumen drainage from the GD ceiling is curtailed and wall slopes decline as lateral growth continues. The main objectives then become improving energy efficiency and reducing energy costs, so the production can be sustained for the longest period (or highest bitumen recovery) before reaching the economic limits of the process (the end of the decline phase). This objective can be achieved by:

(i) Increasing the oxygen/steam ratio to increase the energy supplied by oxygen (per unit energy delivered to the reservoir, oxygen is about a third the cost of steam). A limit of oxygen/steam is about 1.0 (i.e. 50% oxygen) to retain enough steam for effective heat transfer.
(ii) Lowering the target pressure. Saturated steam is more effective at lower pressures (Figure 3). Oxygen combustion effectiveness is independent of pressure (combustion T is not P dependent)

(4) Shut Down – when SAGDOX has reached its economic limit, there is a significant steam inventory, still in the GD chamber, that can be used to transfer heat to peripheral bitumen. The objective is to drain as much of the remaining bitumen as possible while minimizing costs. The procedure is suggested as:

(i) Shut off steam injection. Steam is the most costly energy to inject. Residual steam/water in the reservoir can still be used for good heat transfer.

(ii) Continue operating with oxygen only, until the economic limit is reached. then shut off the oxygen.

(iii) Continue to operate the pattern using the horizontal producer and residual heat in the reservoir. Operate until the new economic limit (using pumping costs as the determinate) is reached.

Example 3 - SAGDOX Control in a Leaky Reservoir

A leaky bitumen reservoir is one that produces an unusual amount of water based on either actual WRR performance, prior geological knowledge or a cold-water injectivity test prior to EOR start-up. There are three kinds of bitumen reservoir concerns - top water, bottom water, or interspersed WLZ.

SAGDOX operation in leaky reservoirs has the following elements:

(1) Start-up – The objectives and procedures are similar to the non-leaky reservoir case except that for a leaky reservoir it may not be possible to achieve pressure targets if pressure targets are significantly higher than native reservoir pressures. Pressure targets may have to be replaced by WRR targets. If the target is WRR = 1.1, and if the actual WRR is lower than this, steam injection is reduced (vice versa for actual WRR higher than the target).

(2) Growth – The objectives and procedures are similar to non-leaky reservoirs, except for the following:

(i) P targets are converted to WRR targets. Pressure should not be less than native reservoir P.

(ii) If a top water problem is suspected, SAGDOX can be used to alter the shape of the GD gas chamber and increase bitumen recovery prior to top water breakthrough. The PG vent wells can be adjusted to increase retention of a non-condensable combustion gas near the top of the reservoir. This can slow down vertical growth rates and change the aspect ratio of GD chamber growth to accelerate lateral growth. The chamber shape will be stretched laterally and delay top water break through.

(iii) If partial interspersed WLZ is suspected and the location is known or suspected, SAGDOX can change conformance by adjusting PG vent well production rates to keep the GD chamber away from the WLZ.

(iv) Influx rates from water lean zones can be reduced by matching pressures or controlling to a WRR target. SAGDOX can retain good bitumen productivity at low pressures because combustion temperatures are independent of pressure. Process T can be higher than saturated steam T.

(3) Decline – The objective is to improve energy efficiency, reduce energy costs and minimize leaks. The end of this phase is achieved at the economic limit. Methods are similar to the non-leaky bitumen reservoir, with the following exceptions:

(i) The target pressure is lowered, and injection control is shifted to WRR control, subject to minimum pressures at/near native reservoir pressure

(ii) The oxygen/steam ratio is increased gradually until the oxygen/steam ratio is about 1.0(v/v), subject to WRR control

(4) Shut down – The objective is to take advantage of the residual heat inventory in the bitumen reservoir. The methods are identical to the non-leaky reservoir, except that:

(i) Oxygen injection is continued but with the constraint on WRR – to allow no or little leaks in or out of the GD chamber.

(ii) Oxygen injection is stopped at the economic limit.

(iii) The producer well is operated until it reaches its economic limit.

Figure 28 depicts 1) how the process will make use of bitumen in WLZ and 2) the net bitumen in the WLZ recovered. The break-even point for the process is at 5.5% bitumen in WLZ.

Tables

Table 1:
Steam + Oxygen Mixtures

% (v/v) Oxygen in Mixture							
	0	5	9	35	50	75	100
% heat from O_2	0	34.8	50.0	84.5	91.0	96.8	100
BTU/SCF Mix	47.4	69.0	86.3	198.8	263.7	371.9	480.0
MSCF/MMBTU	21.1	14.5	11.6	5.0	3.8	2.7	2.1
MSCF O_2/MMBTU	0.0	0.7	1.0	1.8	1.9	2.0	2.1
MSCF Steam/MMBTU	21.1	13.8	10.6	3.3	1.9	0.7	0.0

Where:

(1) Steam heat value = 1000 BTU/lb (avg.)
(2) O_2 heat value = 480 BTU/SCF (Butler (1991))
(3) 0% oxygen = pure steam

Table 2:
Lean Zone Thermal Conductivities

	[W/m°C]
Lean Zone	2.88
Pay Zone	1.09

Where:

1. Lean zone = 80% water saturation; pay zone = 80% oil saturation
2. $\phi = 0.35$
3. Algorithm as per Butler (1991) for sandstone (quartz) reservoir.

Table 3:
Lean Zone Heat Capacities

Heat Capacity	Pay Zone	Lean Zone	% Increase
(kJ/kg)	1.004	1.254	24.9
(kJ/m^3)	2071.7	2584.7	24.8

Where:
1. Uses Butler's algorithms for Cp of bitumen, water, sandstone (Butler (1991).
2. Assumes API = 8.0 S.G. = 1.0143
3. Assumes T = 25°C
4. Pay zone = 35% porosity with 80% bitumen saturation
5. Lean zone = 35% porosity with 80% water saturation

Table 4:
Assumptions for SAGD Simulations

1. Homogeneous Reservoir

- EXOTHERM™ (CMG) SAGD model
- Homogeneous reservoir, no impairments
- Generic properties for bitumen
- 25m net pay; 800m horizontal wells; 100m spacing; 5m separation
- 10°C sub cool control for fluid production
- 3 MPa pressure for steam injection control
- 4 months start up using steam circulation
- Discretized well bore model

2. Leaky Reservoir

- EXOTHERM™ (CMG) SAGD model
- 30m net pay; dual well pairs
- A limited (contained) WLZ
- Remaining reservoir $K_h = 5D$; $K_v = 2.5D$; $S_o = 0.8$
- WLZ – $S_o = 0.15$; $S_w = 0.85$; 6m thick (10% of pay zone volume)

- In the main reservoir, Sw = 0.20; 0.15 irreducible; 0.05 mobile.
- 2 MPa target pressure for both pairs
- 10°C sub cool control

Case 1 – as above, same P in both well pairs, 6m thick WLZ
Case 2 – allow 300 kPa ΔP between well pairs
Case 2(a) – extend production forecast to 3+ years
Case 3 – same as 2, but shift to volume control (drop P control) after 1 yr.
Case 4 – same as 2, but with 3m thick WLZ (5% of pay zone volume)
Case 5 – Same as 3, but with 3m thick WLZ

Claims

1. A method to operate a Steam Assisted Gravity Drainage with Oxygen (SAGDOX) process, in a leaky bitumen reservoir, wherein said SAGDOX process comprises a start-up phase, growth phase, decline phase and shut down phase, said method comprising, at the start-up phase:

   (1) Circulating steam in two horizontal Steam Assisted Gravity Drainage (SAGD) wells, until communication is established between said two horizontal SAGD wells,
   (2) Injecting and optionally circulating steam in a SAGDOX oxygen injector well and vent gas well until communication is established,
   (3) Switching the horizontal wells to operate in a SAGD mode, with the upper well as a steam injector and the lower well as a fluid producer, creating a steam chamber,
   (4) Starting oxygen injection in the SAGDOX oxygen injector well, with O_2/steam (v/v) ratios of from about 0.05 to about 0.15, and
   (5) Opening at least one Produced Gas (PG) vent gas well, until steam injection is substantially limited to the upper horizontal well, oxygen injection has started and PG vent gas removal has started.

2. A method to operate a SAGDOX process, in a leaky bitumen reservoir, wherein said SAGDOX process comprises a start-up phase, growth phase, decline phase and shut down phase, in the growth phase of the process, preferably to increase/optimize bitumen productivity and preferably to achieve a WRR target for the process, said method comprising:

   (1) Adjusting oxygen/steam ratios (v/v),
   (2) Adjusting energy injection rates (steam + oxygen) by controlling volumes and ratios,
   (3) Adjusting vent gas well rates, and

(4) Adjusting production well sub-cool targets, until bitumen productivity peaks.

3. A method to operate a SAGDOX process, in a leaky bitumen reservoir, wherein said SAGDOX process comprises a start-up phase, growth phase, decline phase and shut down phase, in the decline phase of the process, preferably resulting in at least one of improving energy efficiency, reducing costs, maximizing bitumen recovery and achieving a WRR target, comprising:

(1) Increasing the oxygen/steam (v/v) ratio, preferably to a maximum of 1.0,
(2) Adjusting PG vent gas rates,
(3) Adjusting energy injection rates (steam + oxygen) by controlling volumes and ratios, and
(4) Adjusting production well sub-cool targets, preferably until economic limit for the SAGDOX process is substantially achieved.

4. A method to operate a SAGDOX process in a leaky bitumen reservoir, wherein said SAGDOX process comprises a start-up phase, growth phase, decline phase and shut down phase in the shut-down phase of the process, preferably maximizing economic bitumen recovery, comprising:

(1) Shutting off steam injection,
(2) Adjusting oxygen injection rates,
(3) Shutting off oxygen injection upon substantially achieving final economic limit, and
(4) Continuing residual bitumen production until the final economic limit is substantially achieved.

5. The method of claims 1-4, wherein said SAGDOX process has system pressures selected from the group consisting of less than reservoir parting pressure, greater than native reservoir pressure, and substantially equal to native reservoir pressure.

6. The method of claims 1-4, wherein the SAGDOX process pressure targets are replaced by Water Recycle Ratio (WRR) targets.

7. The method of claim 6, wherein the WRR target is between 0.5 and 1.2.

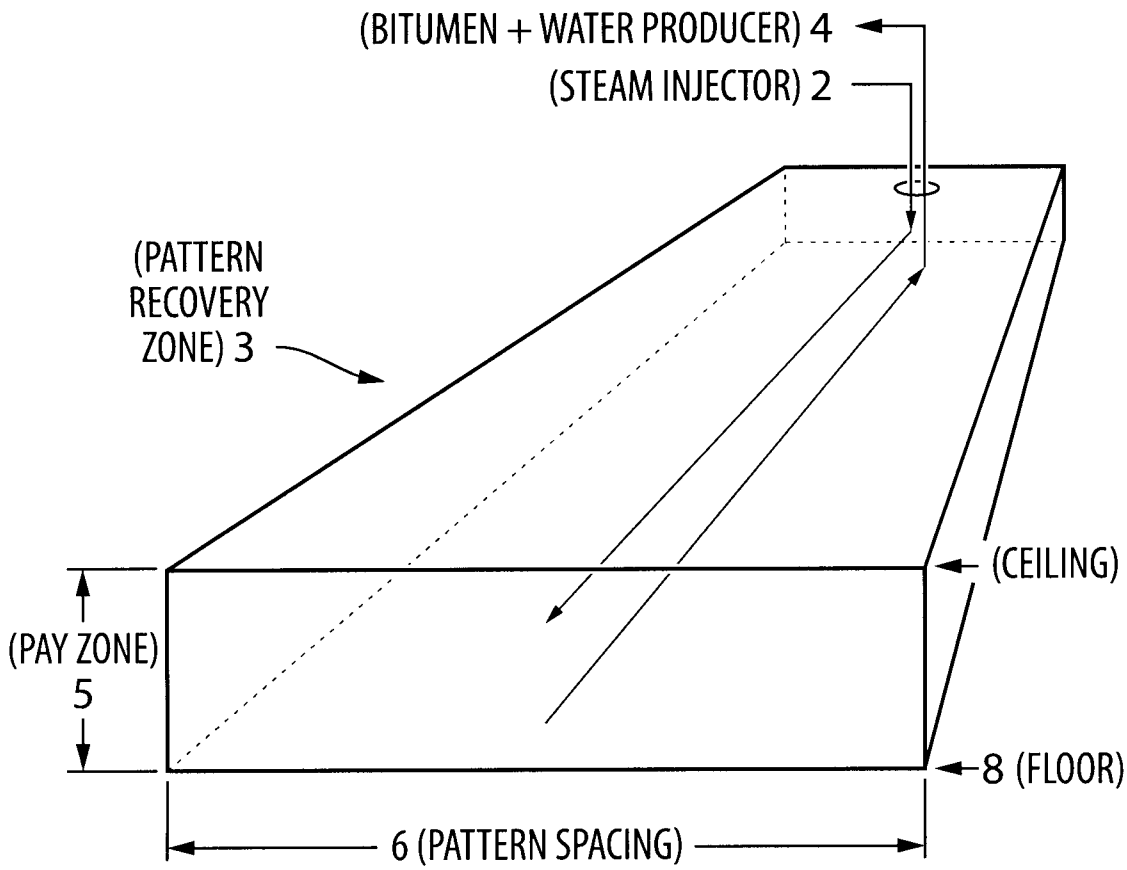
8. The method of claim 7, wherein the WRR target is between 0.8 and 1.2.

9. The method of claim 8, wherein the WRR target is and between 0.9 and 1.2.

10. The method of claims 1-4, wherein the SAGDOX process has a sub cool target between 5°C and 30°C.

11. The method of claims 1-4, wherein said bitumen is a liquid hydrocarbon with API < 10 and viscosity > 100,000 cp.

12. The method of claims 1-4, wherein said leaky bitumen reservoir has a WRR outside the range 0.9 to 1.1, after 200 days or more of SAGDOX operation.



SAGD WELL CONFIGURATION

FIG.1

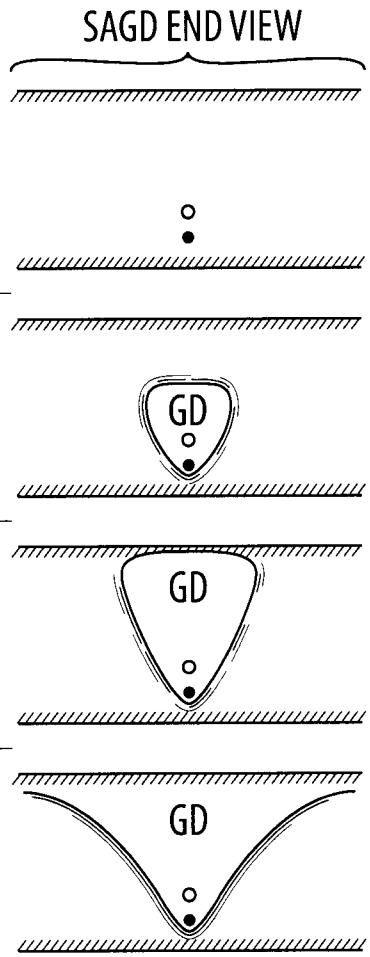
SAGD STAGES

1) **Start-up** - Steam circulation to establish communication between wells.

2) **Growth** - GD chamber grows upward and outward, until it hits net pay ceiling.

3) **Decline** - Lose ceiling drainage, productivity drops.

4) **Shut-down** - Residual bituman drainage.



GD = Gravity Drainage Chamber

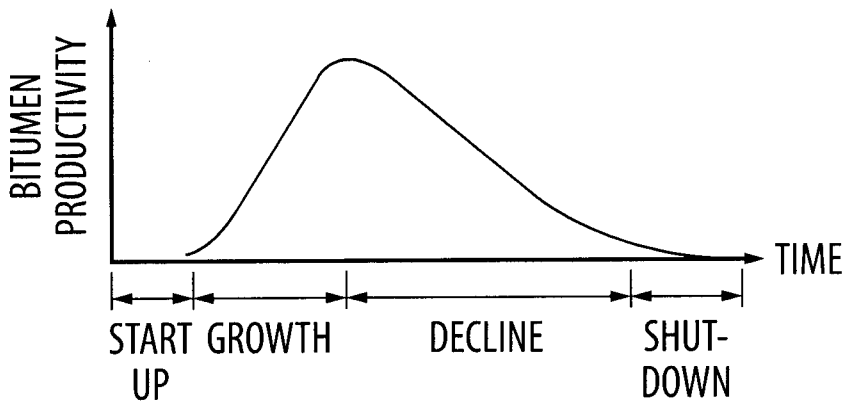
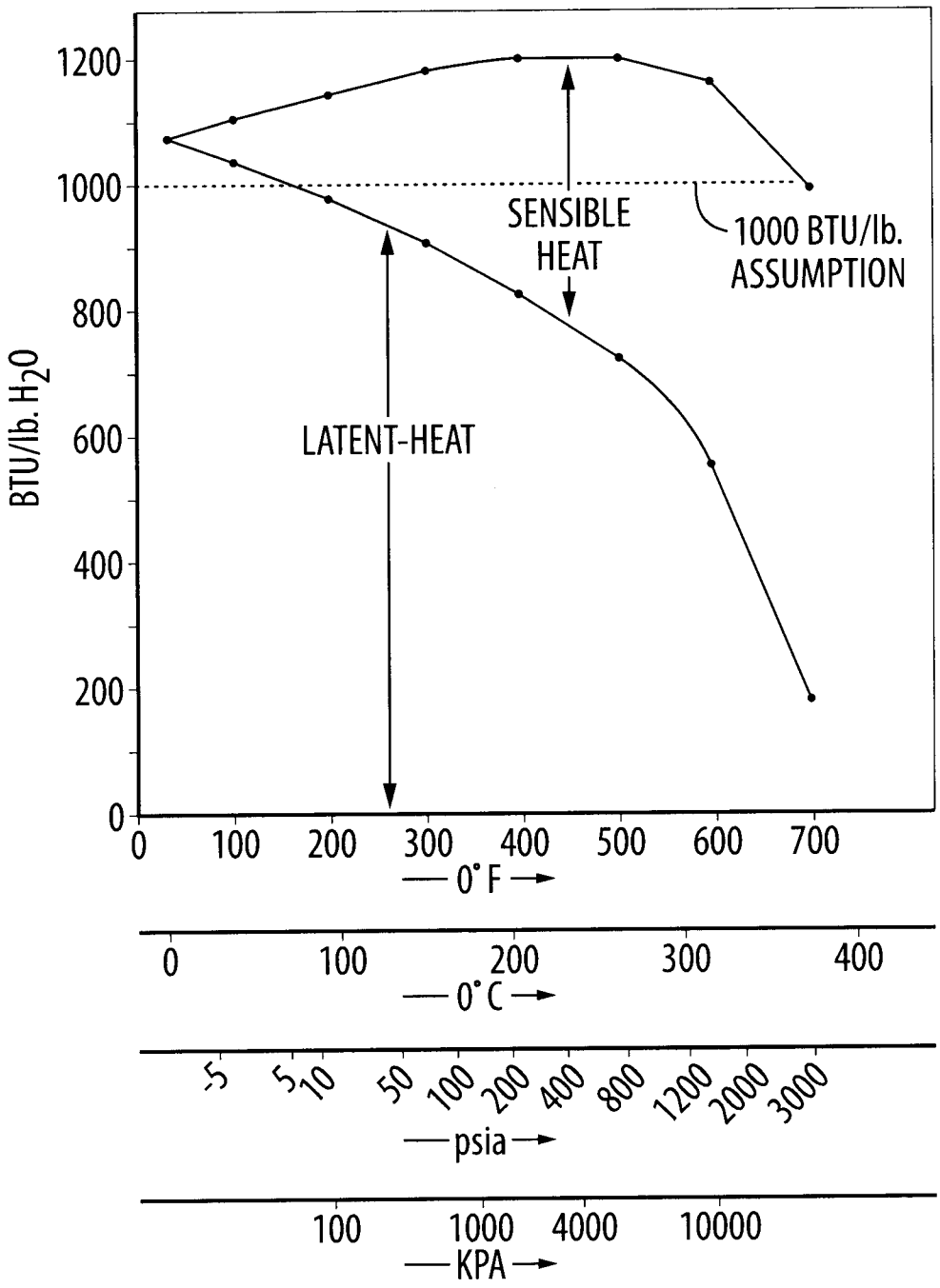
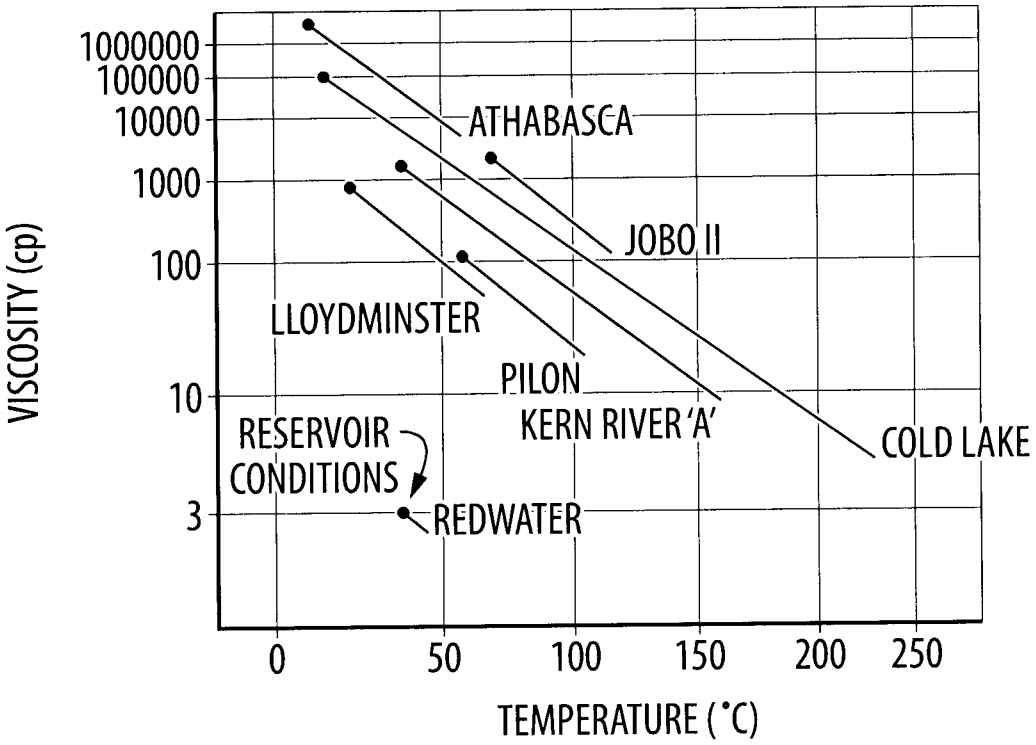


FIG.2



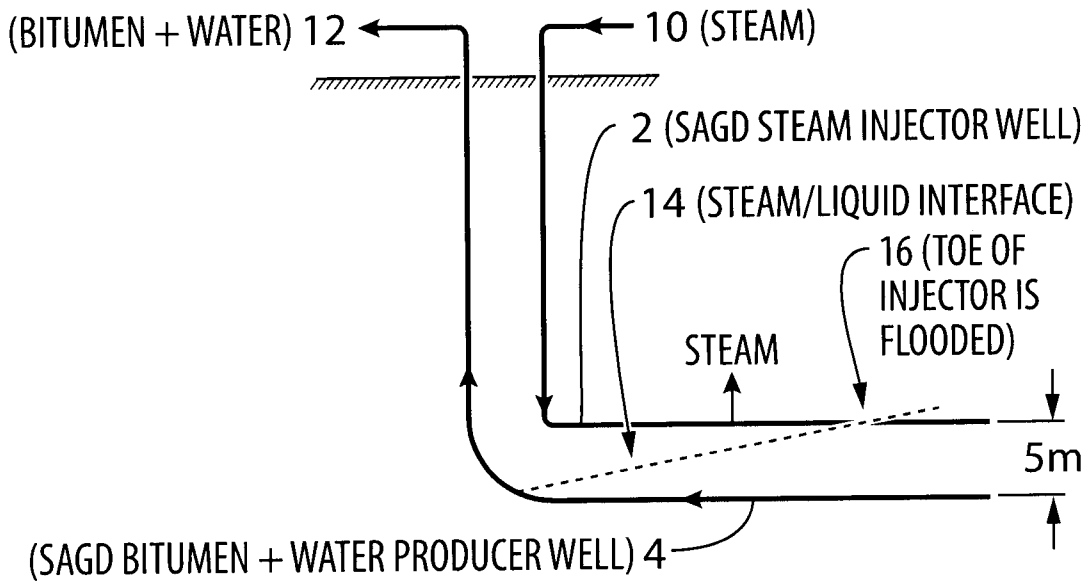
SATURATED STEAM PROPERTIES

FIG.3



BITUMEN + HEAVY OIL VISCOSITIES (BUTLER, 1991)

FIG.4



SAGD HYDRAULIC LIMITS

FIG.5

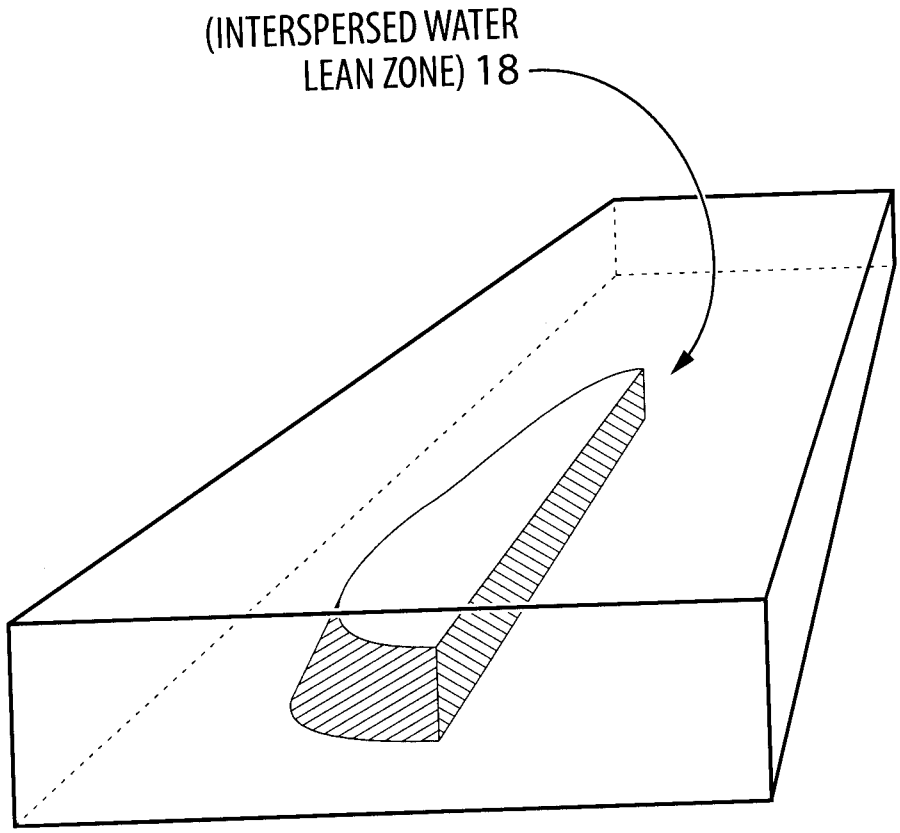
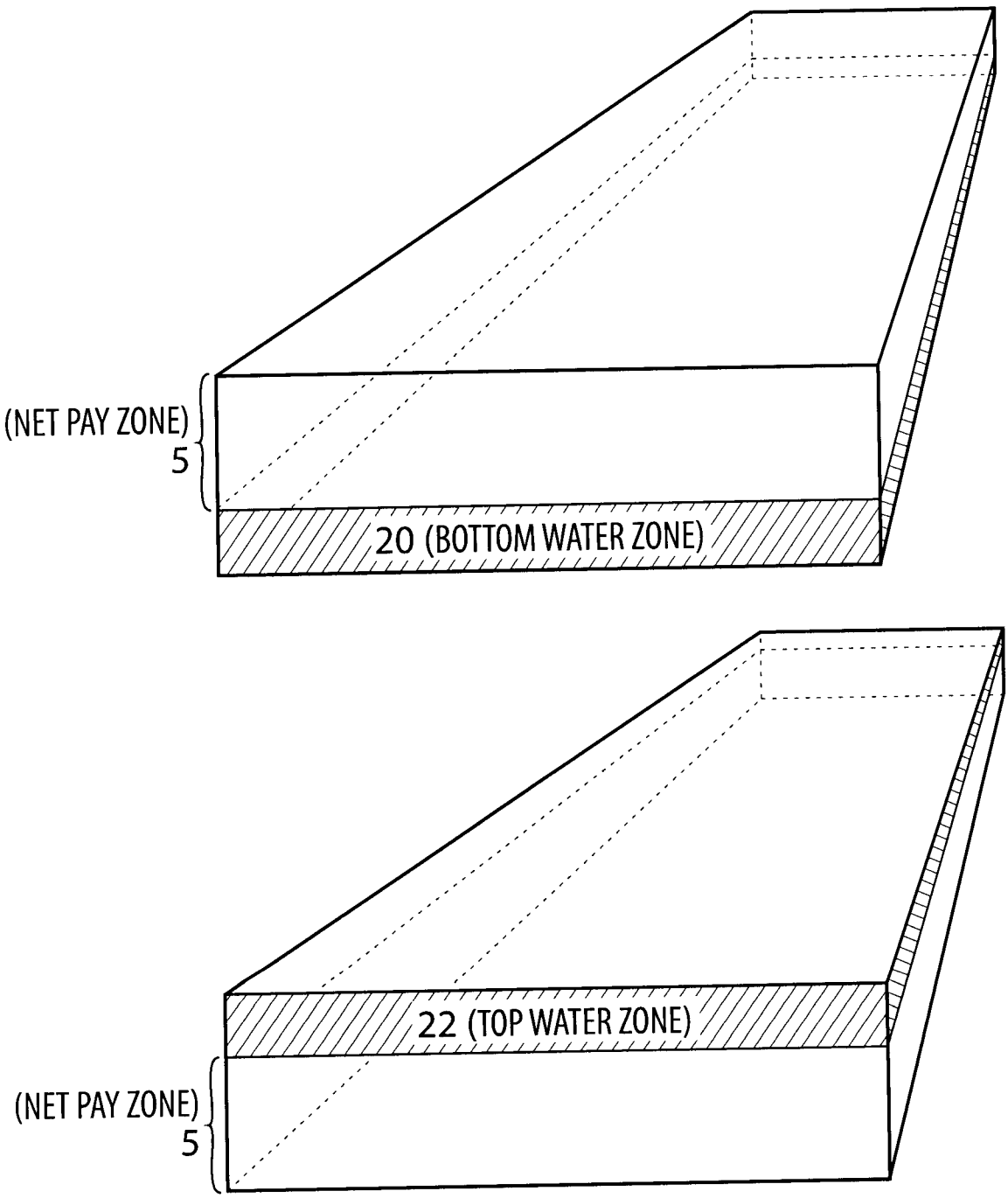
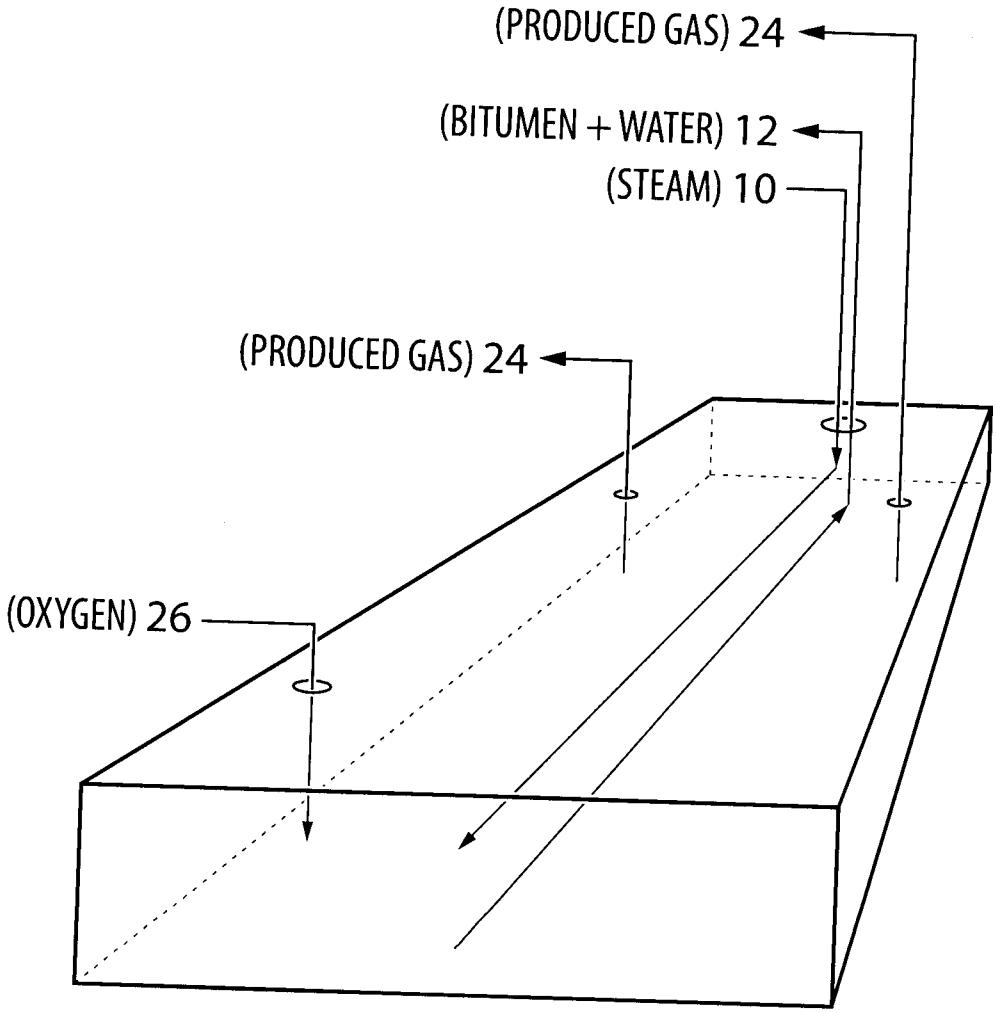

(INTERSPERSED WATER
LEAN ZONE) 18
INTERSPERSED BITUMEN LEAN ZONES

FIG.6



TOP/BOTTOM WATER: OILSANDS

FIG.7


(PRODUCED GAS) 24
(BITUMEN + WATER) 12
(STEAM) 10
(PRODUCED GAS) 24
(OXYGEN) 26

SAGDOX

FIG.8

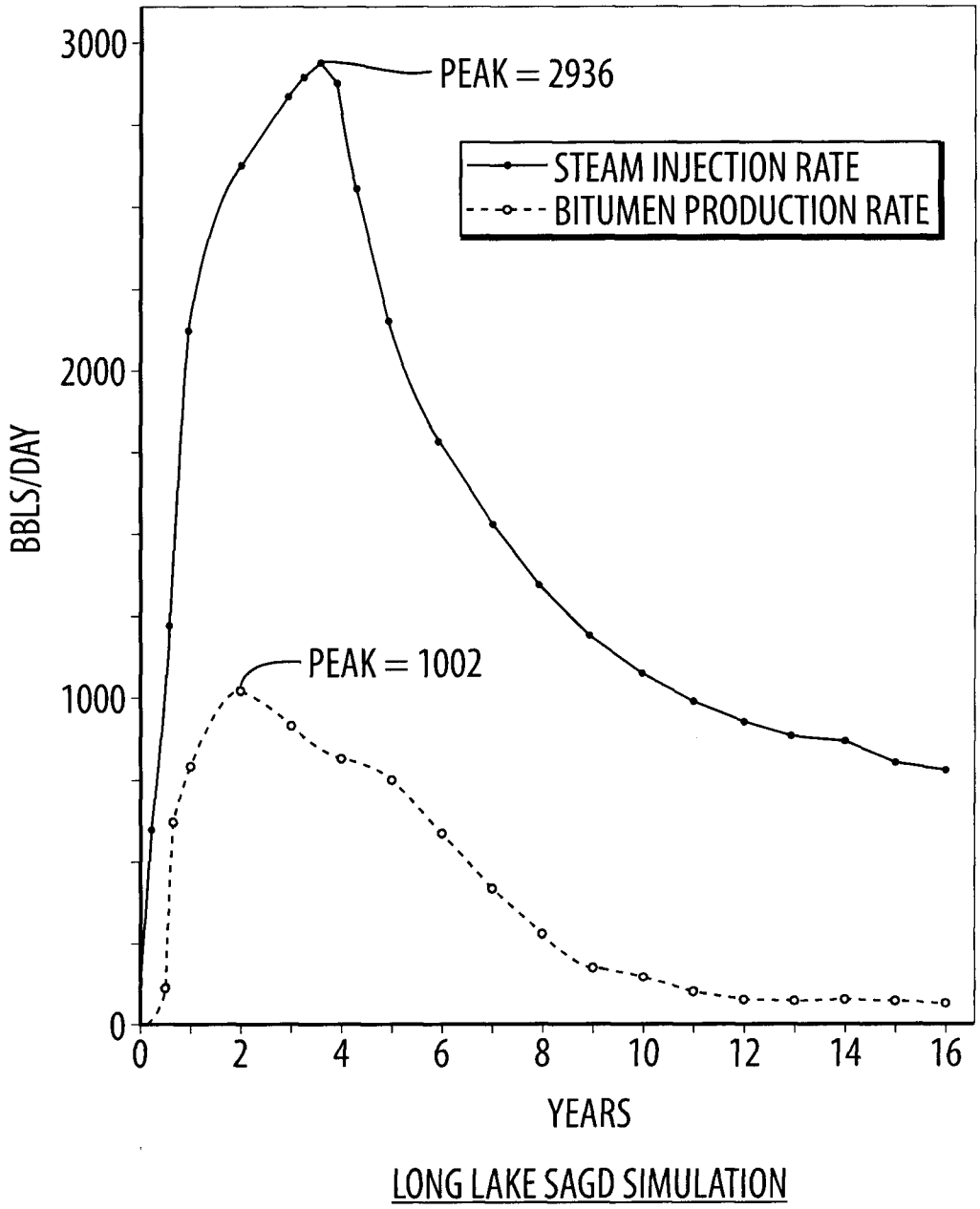
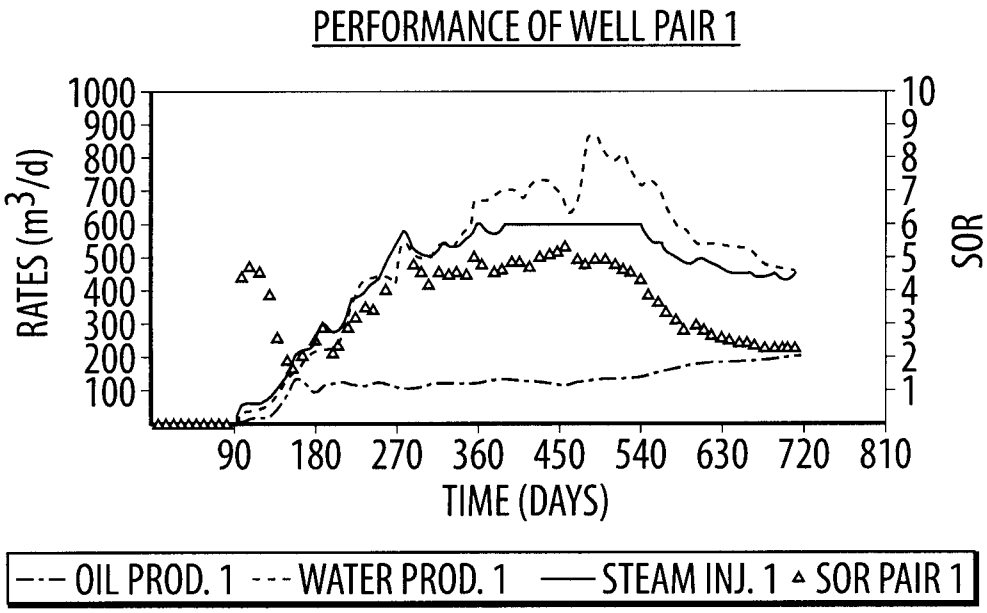

3000
2000
1000
0
BBLS/DAY
PEAK = 2936
STEAM INJECTION RATE
BITUMEN PRODUCTION RATE
PEAK = 1002
0
2
4
6
8
10
12
14
16
YEARS
LONG LAKE SAGD SIMULATION

FIG.9

CASE 1 (BASE CASE): 6m LZ



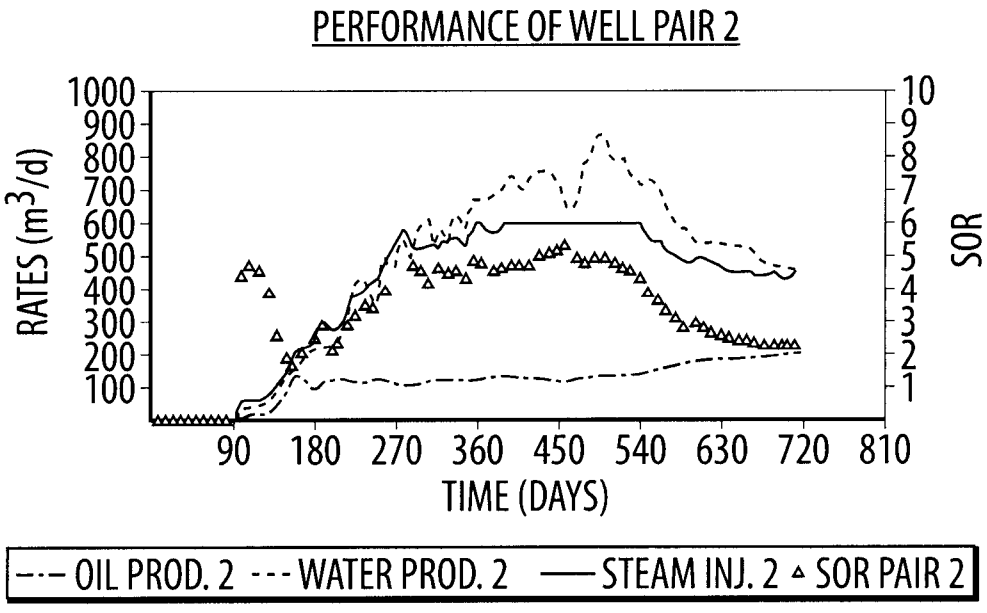


FIG.10

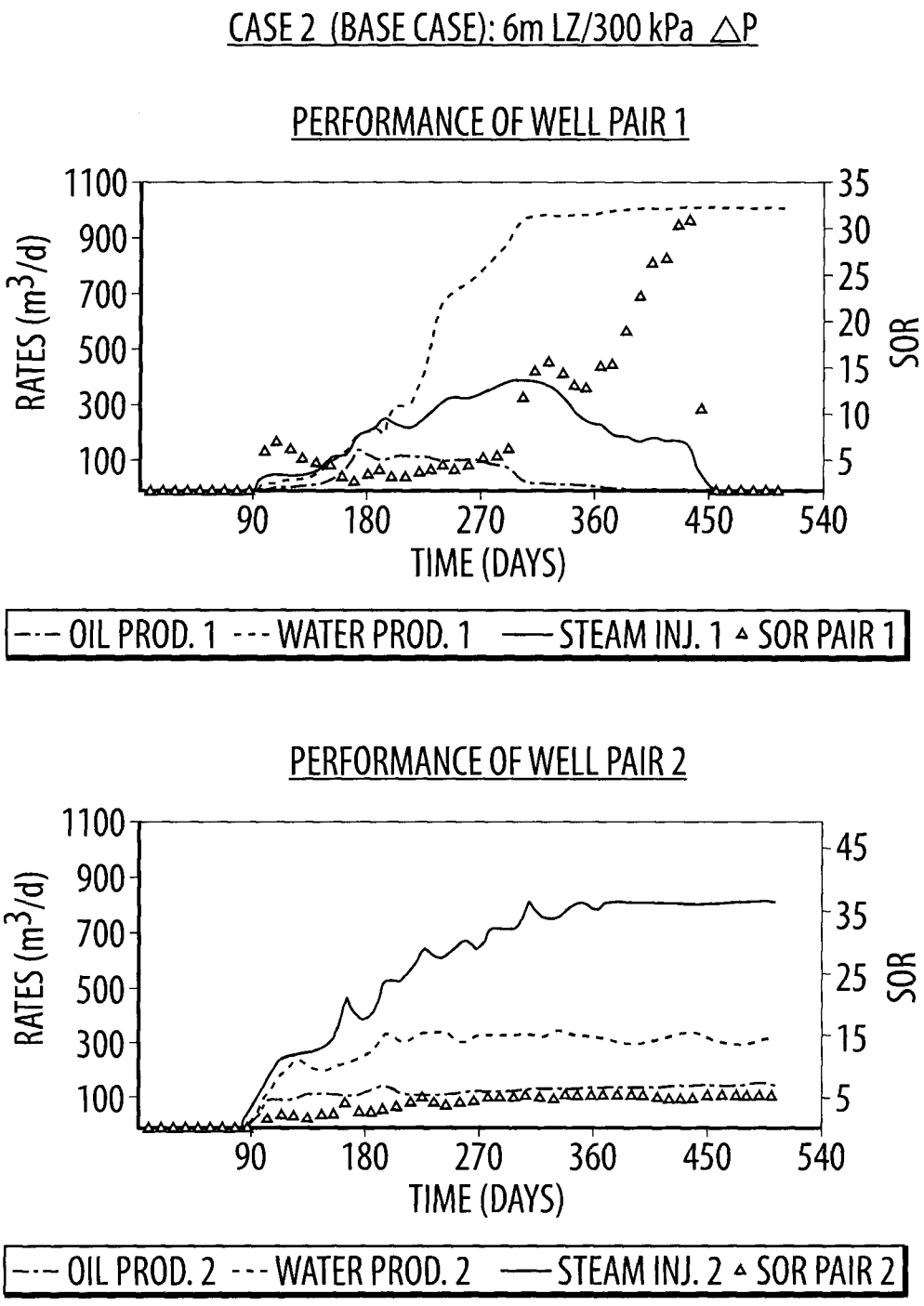
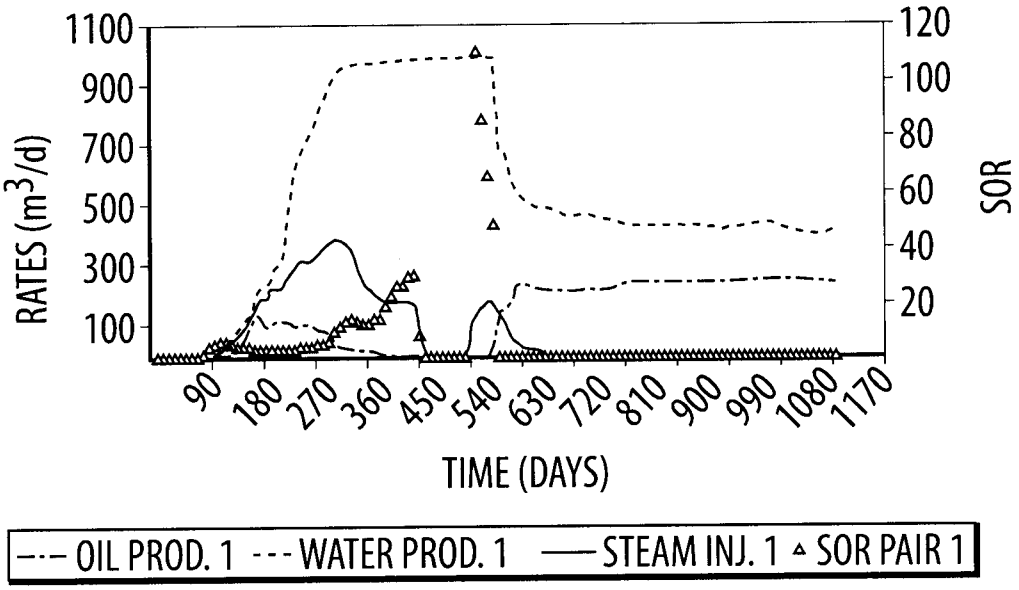

CASE 2 (BASE CASE): 6m LZ/300 kPa △P
PERFORMANCE OF WELL PAIR 1
RATES (m3/d)
1100
900
700
500
300
100
35
30
25
20
15
10
5
SOR
90
180
270
360
450
540
TIME (DAYS)
OIL PROD. 1
WATER PROD. 1
STEAM INJ. 1
SOR PAIR 1
PERFORMANCE OF WELL PAIR 2
RATES (m3/d)
1100
900
700
500
300
100
45
35
25
15
5
SOR
90
180
270
360
450
540
TIME (DAYS)
OIL PROD. 2
WATER PROD. 2
STEAM INJ. 2
SOR PAIR 2

FIG.11

CASE 2(a) 6m LZ/LONG TERM

PERFORMANCE OF WELL PAIR 1



PERFORMANCE OF WELL PAIR 2

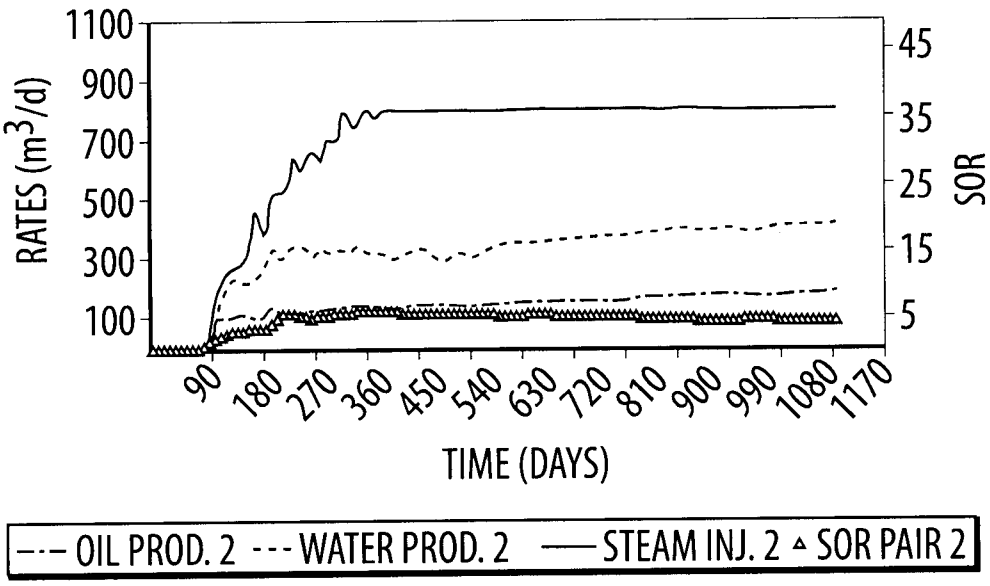
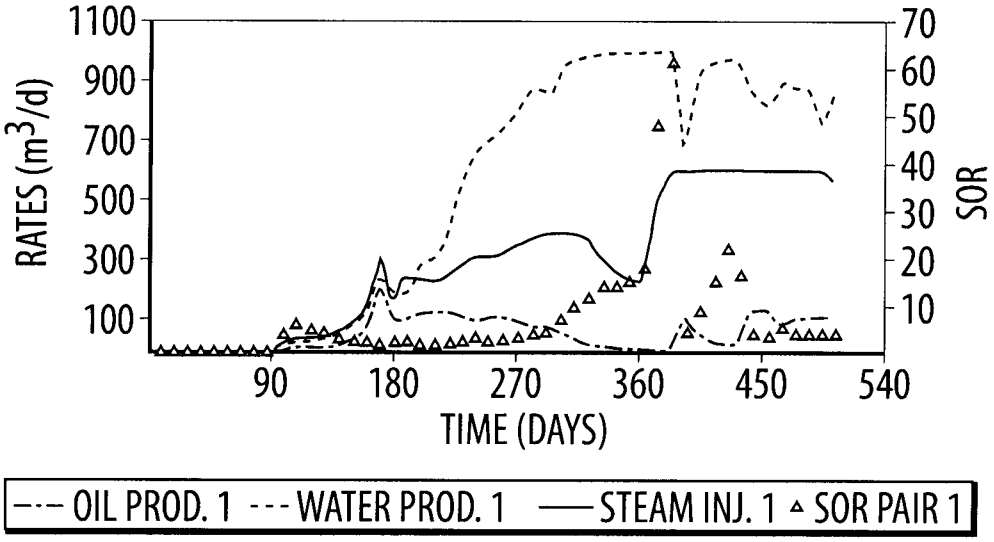


FIG.12

CASE 3: 6m LZ/BALANCE>1YR

PERFORMANCE OF WELL PAIR 1



PERFORMANCE OF WELL PAIR 2

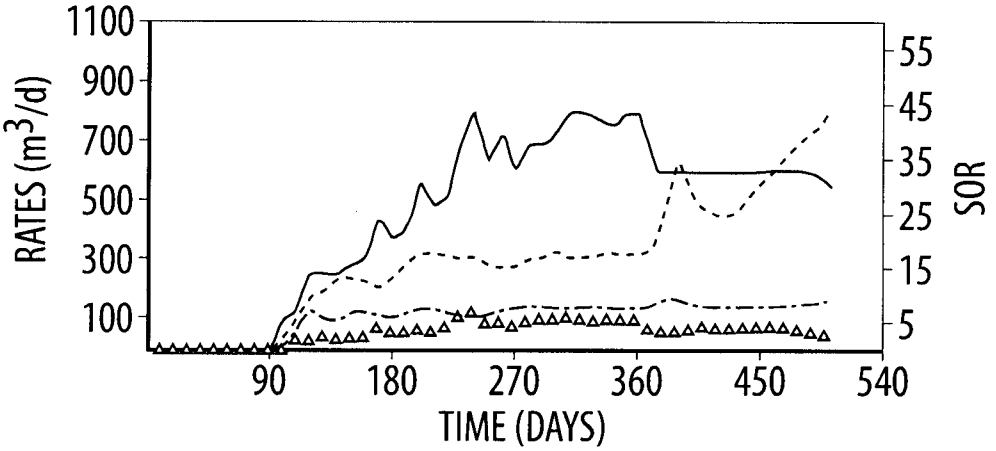


FIG.13

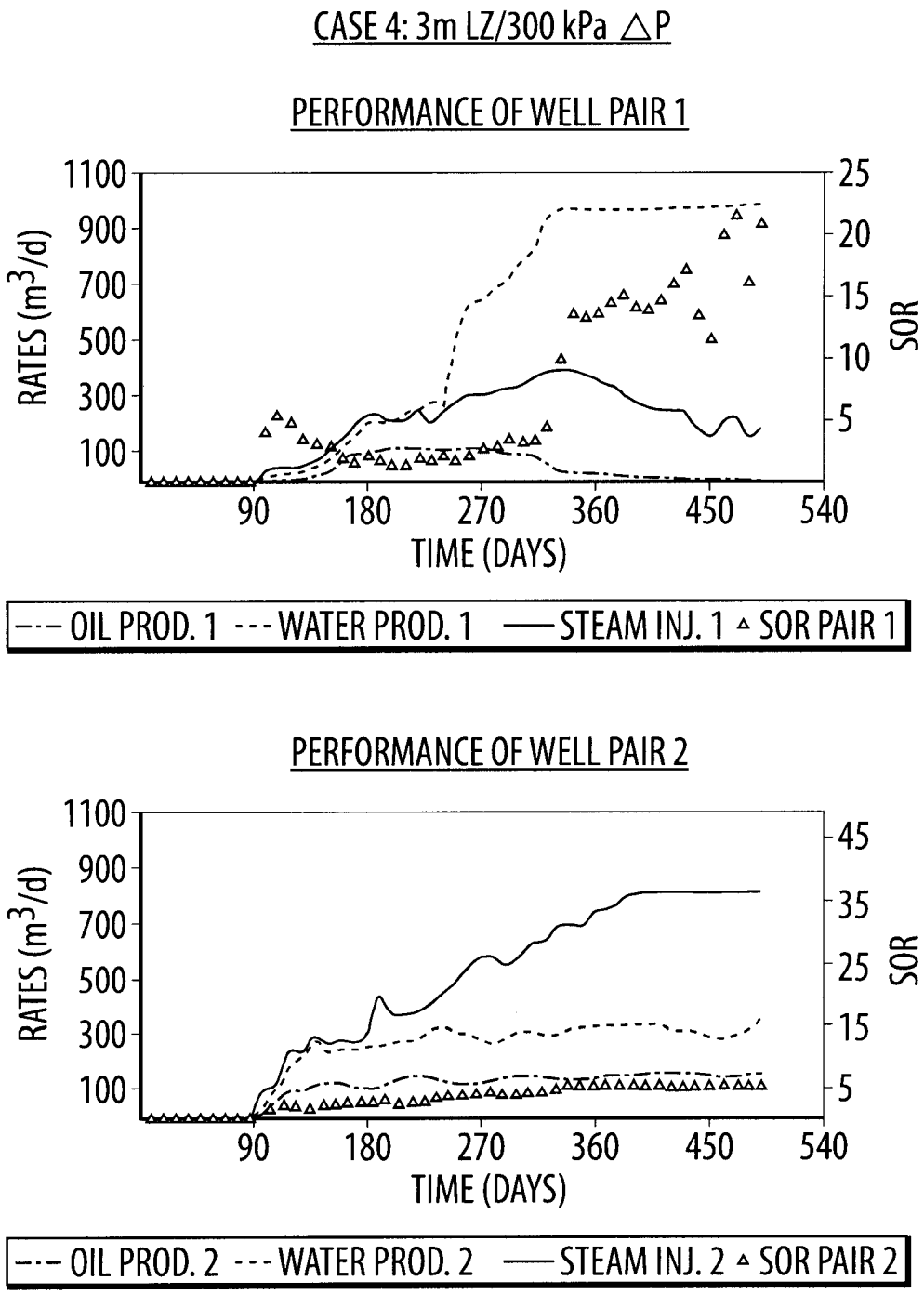
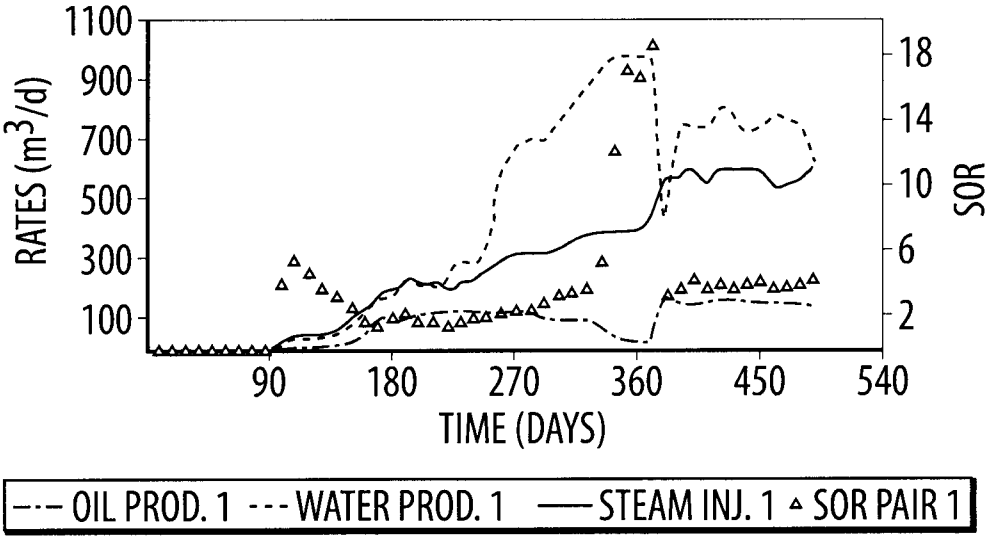

CASE 4: 3m LZ/300 kPa △P
PERFORMANCE OF WELL PAIR 1
RATES (m3/d)
1100
900
700
500
300
100
25
20
15
10
5
SOR
90
180
270
360
450
540
TIME (DAYS)
OIL PROD. 1
WATER PROD. 1
STEAM INJ. 1
SOR PAIR 1
PERFORMANCE OF WELL PAIR 2
RATES (m3/d)
1100
900
700
500
300
100
45
35
25
15
5
SOR
90
180
270
360
450
540
TIME (DAYS)
OIL PROD. 2
WATER PROD. 2
STEAM INJ. 2
SOR PAIR 2

FIG.14

CASE 5: 3m LZ/BALANCE>1YR

PERFORMANCE OF WELL PAIR 1



PERFORMANCE OF WELL PAIR 2

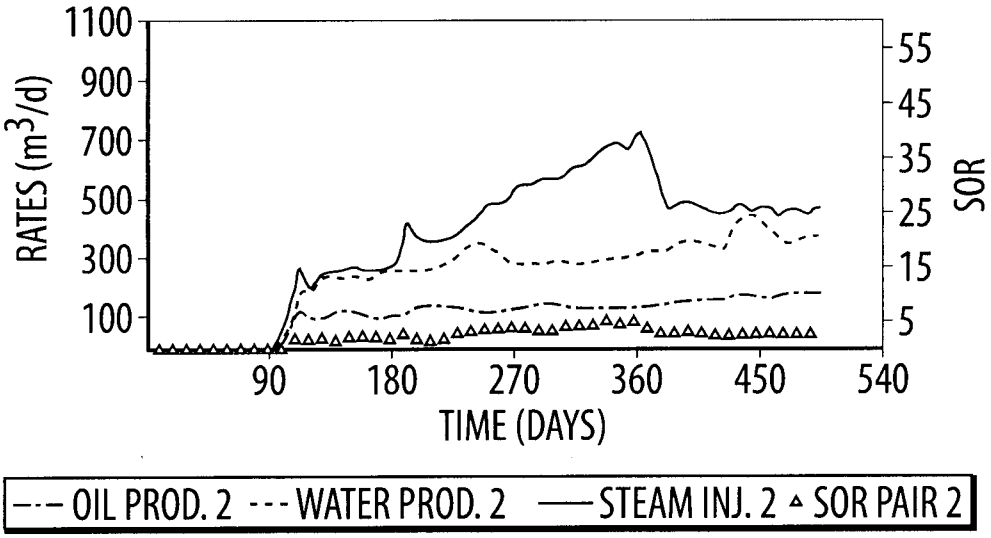


FIG.15

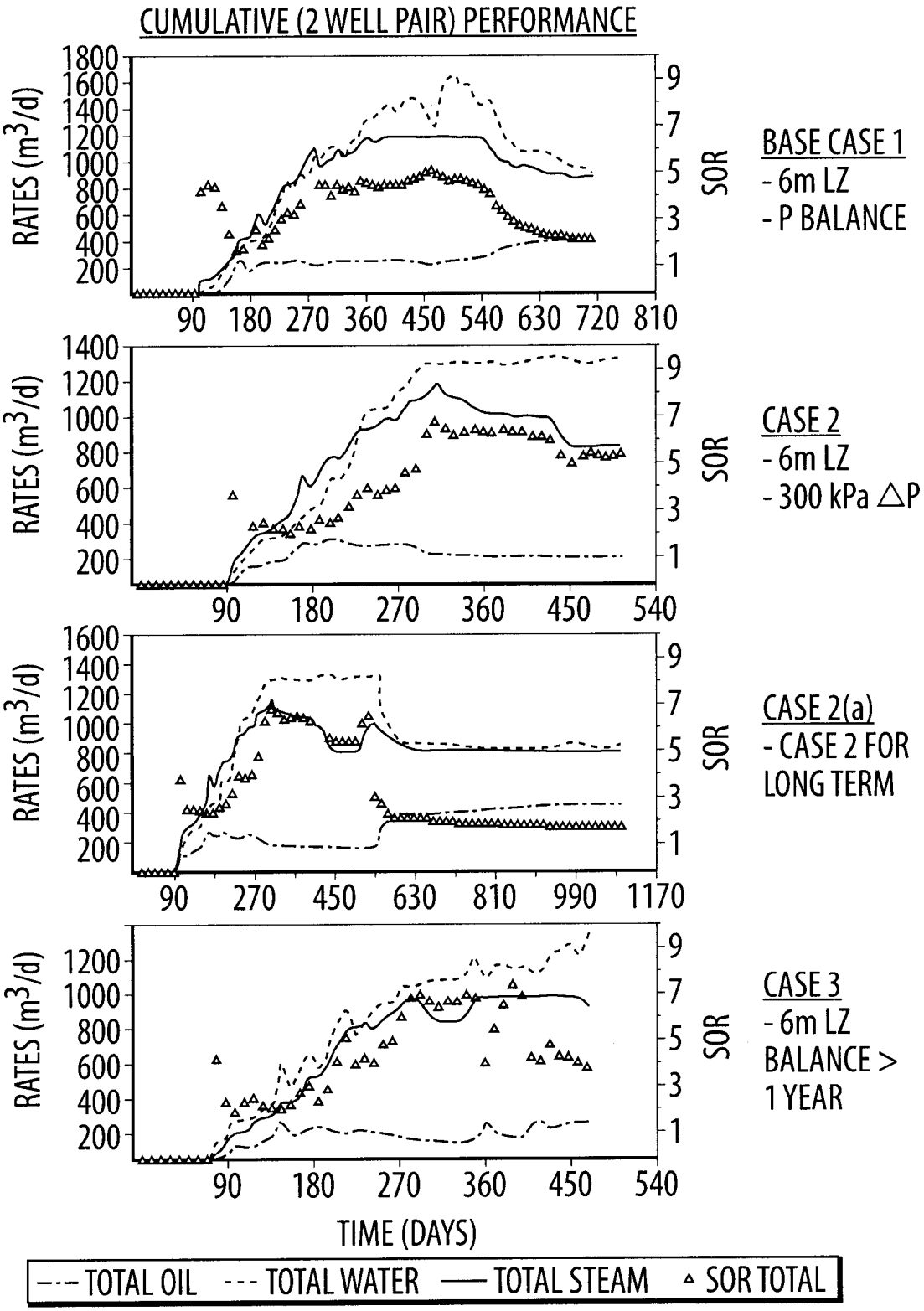

CUMULATIVE (2 WELL PAIR) PERFORMANCE
RATES (m3/d)
SOR
BASE CASE 1
- 6m LZ
- P BALANCE
CASE 2
- 6m LZ
- 300 kPa △P
CASE 2(a)
- CASE 2 FOR LONG TERM
CASE 3
- 6m LZ
BALANCE > 1 YEAR
TIME (DAYS)
TOTAL OIL
TOTAL WATER
TOTAL STEAM
SOR TOTAL

FIG.16

CUMULATIVE (2 WELL PAIR) PERFORMANCE CONTINUED

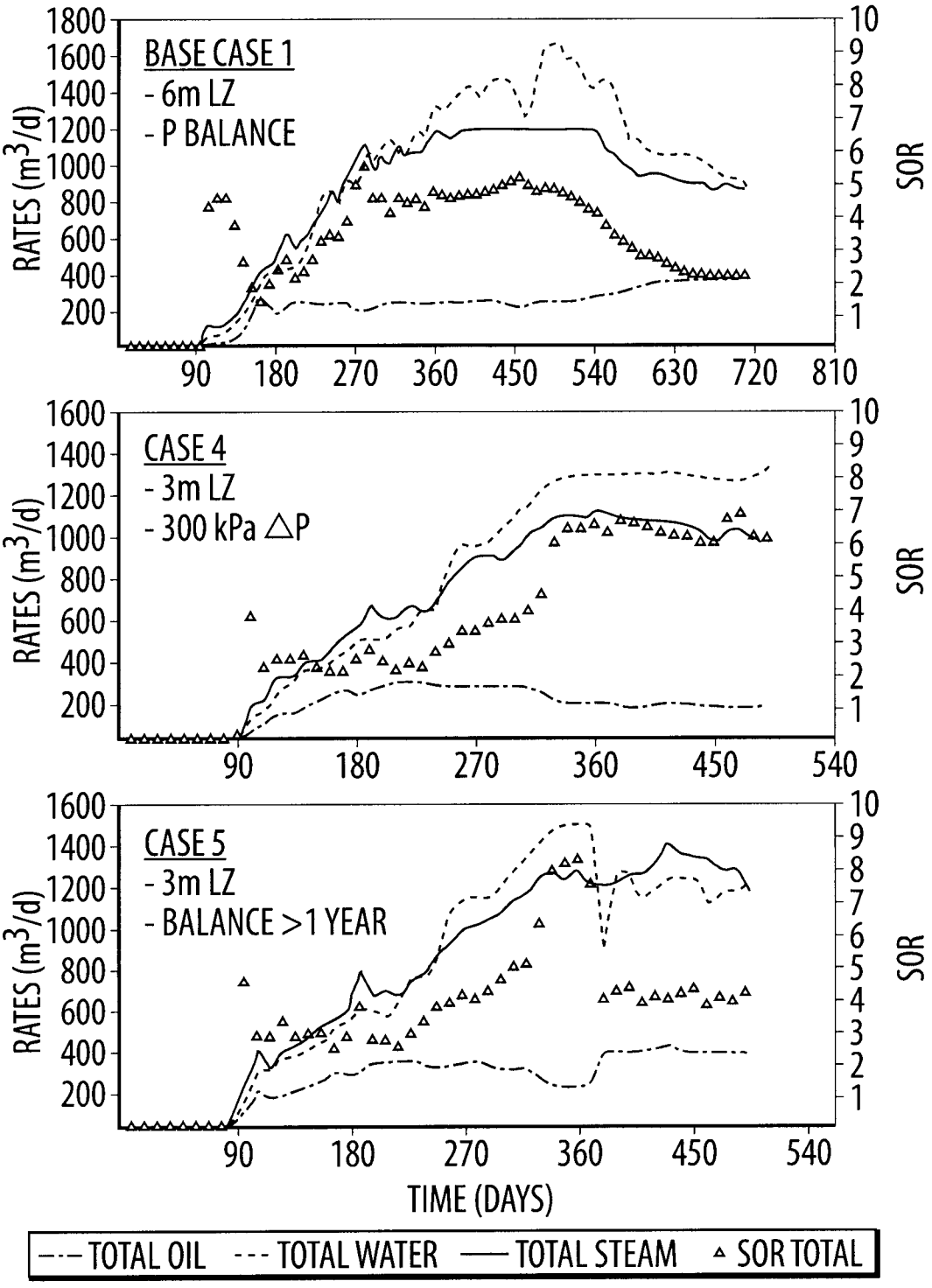
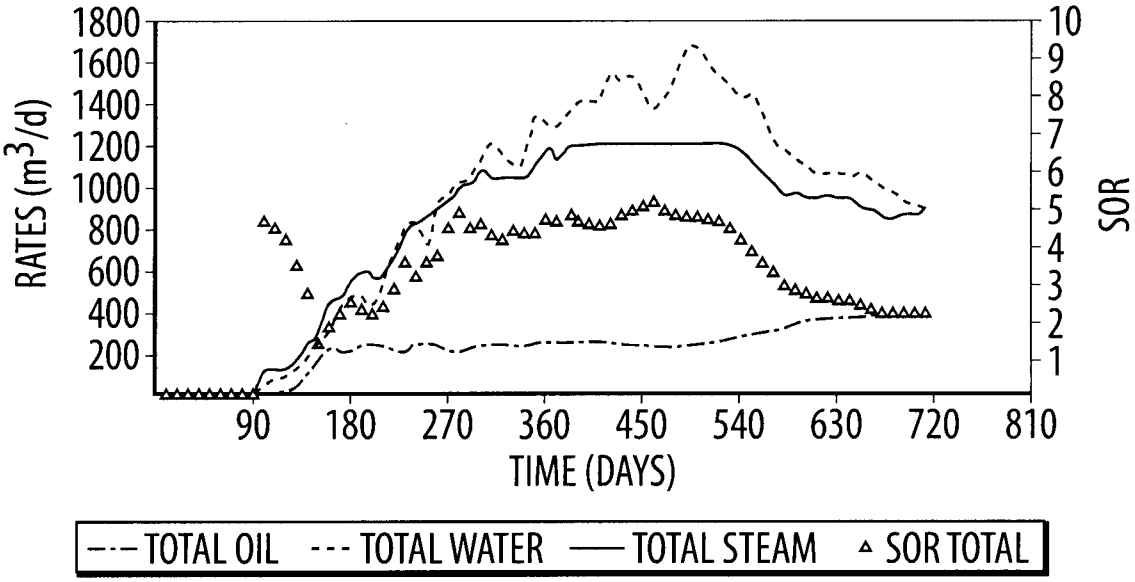


FIG.17

DUAL WELL PAIR PRODUCTION/PERFORMANCE

IMPACT OF CROSSFLOW BETWEEN TWO WELL PAIRS
(BASE CASE - 2000kPa FOR BOTH WELL PAIRS) (PAIR CASE) (NO CROSSFLOW)



IMPACT OF CROSSFLOW BETWEEN TWO WELL PAIRS
(INJ 2 PRESSURE IS 300kPa HIGHER THAN INJ 1 FOR THE 1ST YEAR)
(CROSSFLOW) (CASE 2)

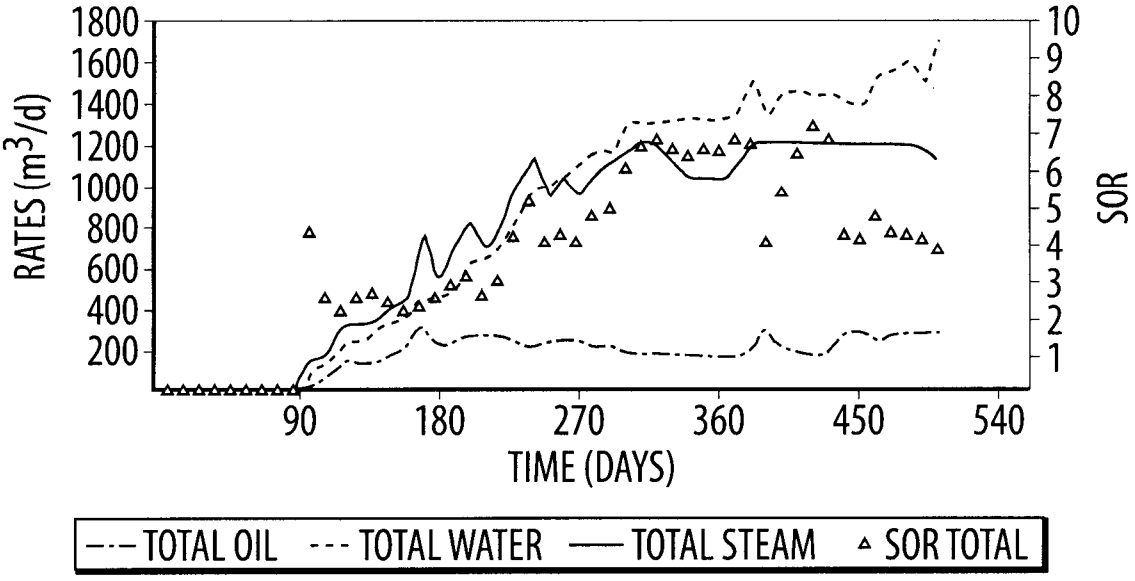


FIG.18

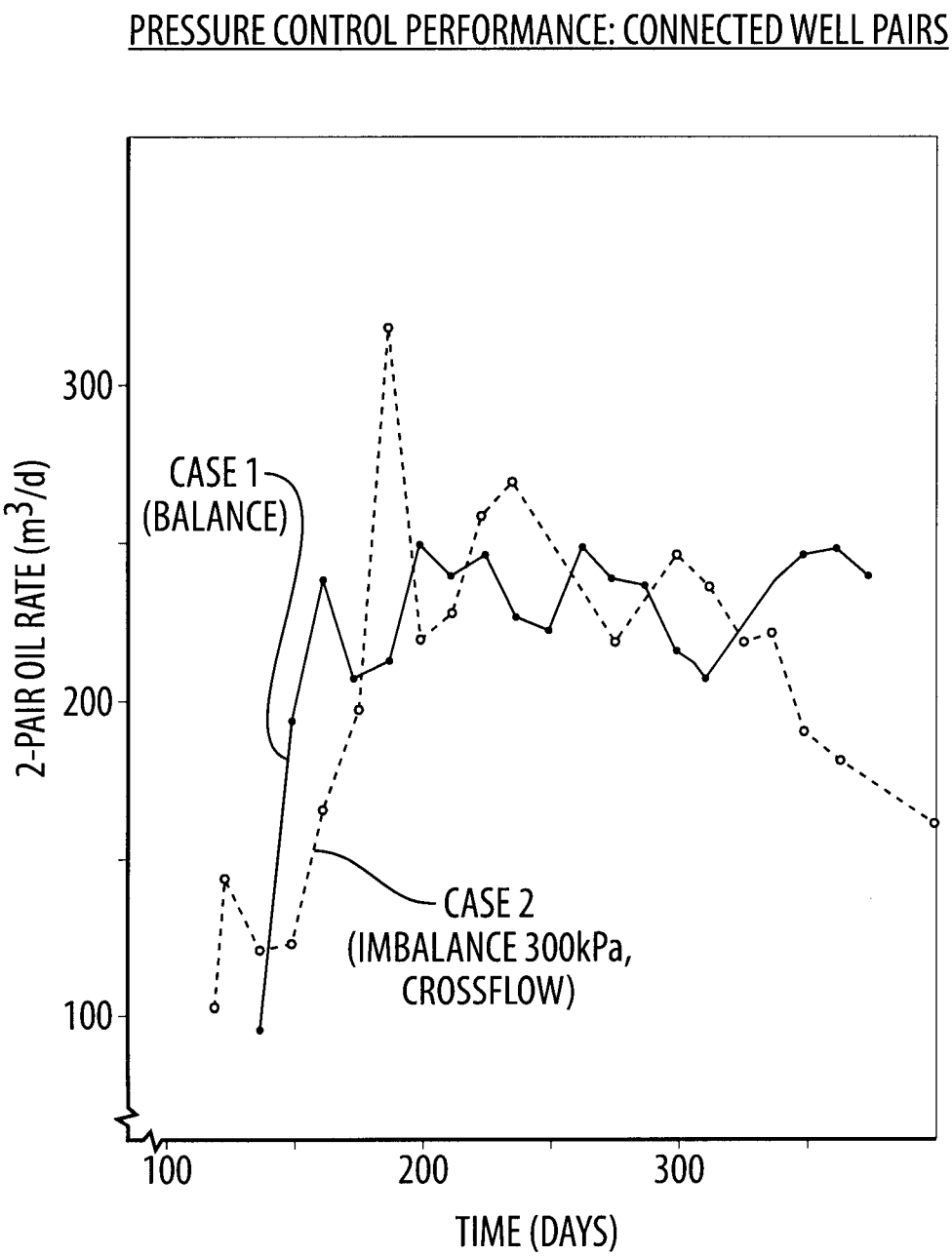

PRESSURE CONTROL PERFORMANCE: CONNECTED WELL PAIRS
2-PAIR OIL RATE (m3/d)
300
200
100
CASE 1
(BALANCE)
CASE 2
(IMBALANCE 300kPa,
CROSSFLOW)
100
200
300
TIME (DAYS)

FIG.19

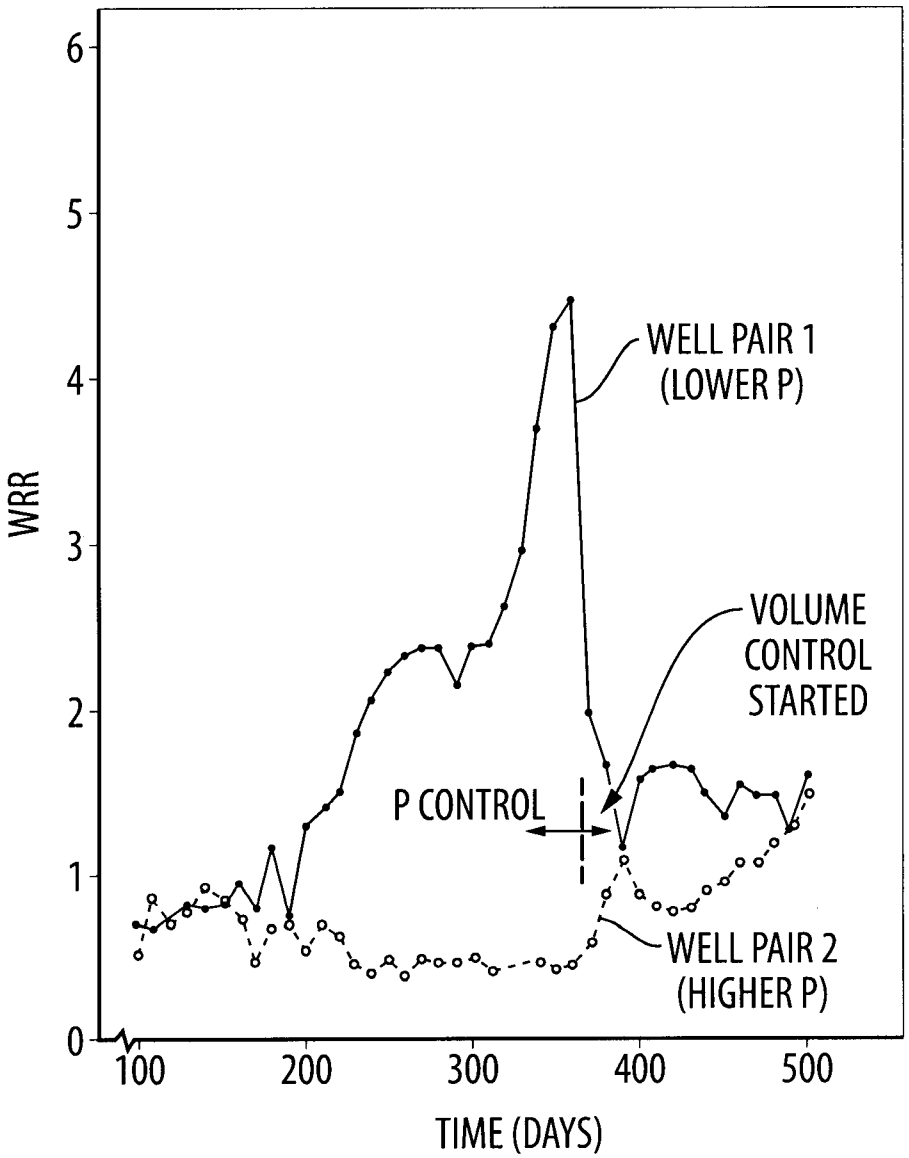

CASE 3 (CROSSFLOW) WRR PERFORMANCE: CONNECTED WELL PAIRS
WRR
TIME (DAYS)
WELL PAIR 1
(LOWER P)
VOLUME
CONTROL
STARTED
P CONTROL
WELL PAIR 2
(HIGHER P)
0
1
2
3
4
5
6
100
200
300
400
500

FIG.20

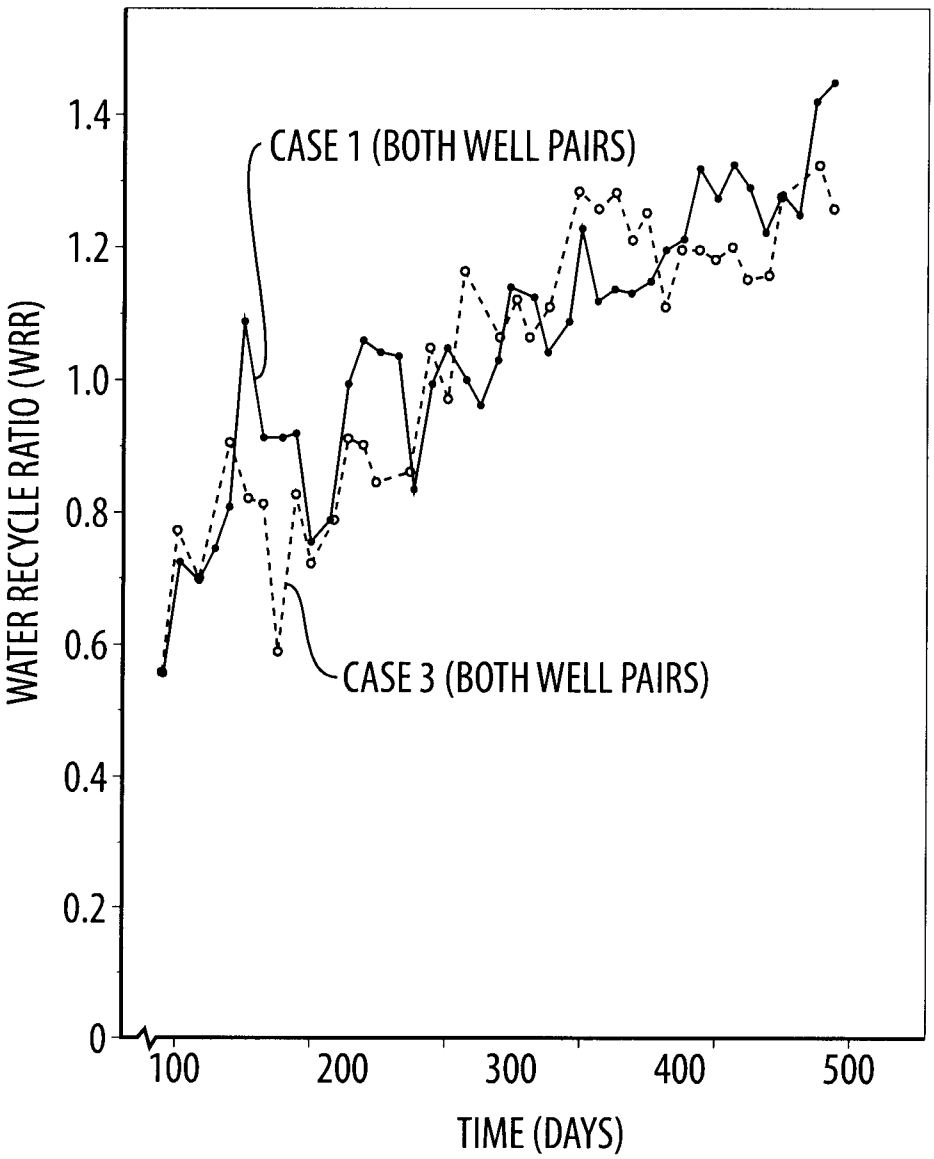

WRR PERFORMANCE: CONNECTED WELL PAIRS
WATER RECYCLE RATIO (WRR)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
CASE 1 (BOTH WELL PAIRS)
CASE 3 (BOTH WELL PAIRS)
100
200
300
400
500
TIME (DAYS)

FIG.21

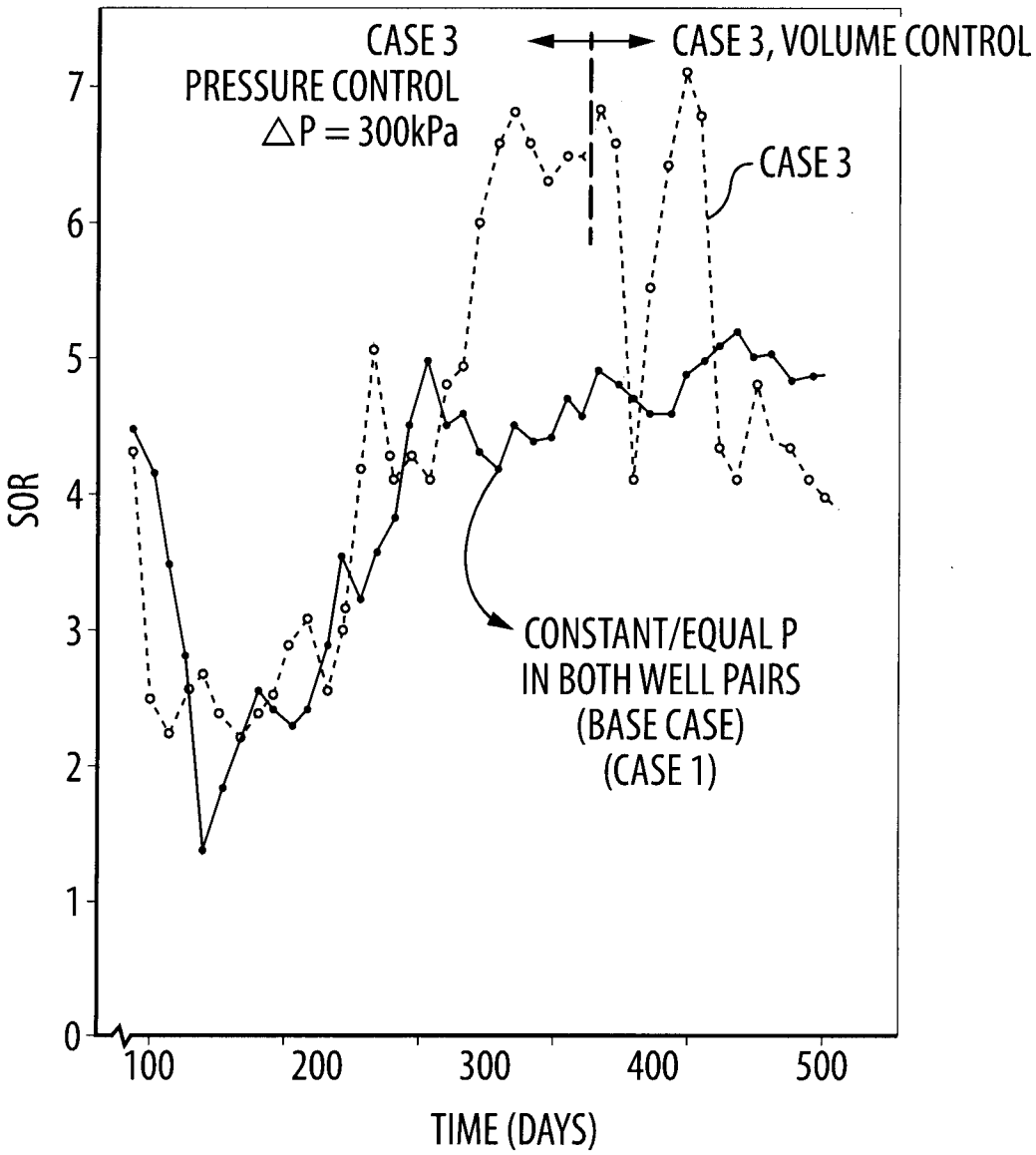

SOR PERFORMANCE
CASE 3
PRESSURE CONTROL
△P = 300kPa
CASE 3, VOLUME CONTROL
CASE 3
CONSTANT/EQUAL P
IN BOTH WELL PAIRS
(BASE CASE)
(CASE 1)
SOR
TIME (DAYS)
0
1
2
3
4
5
6
7
100
200
300
400
500

FIG.22

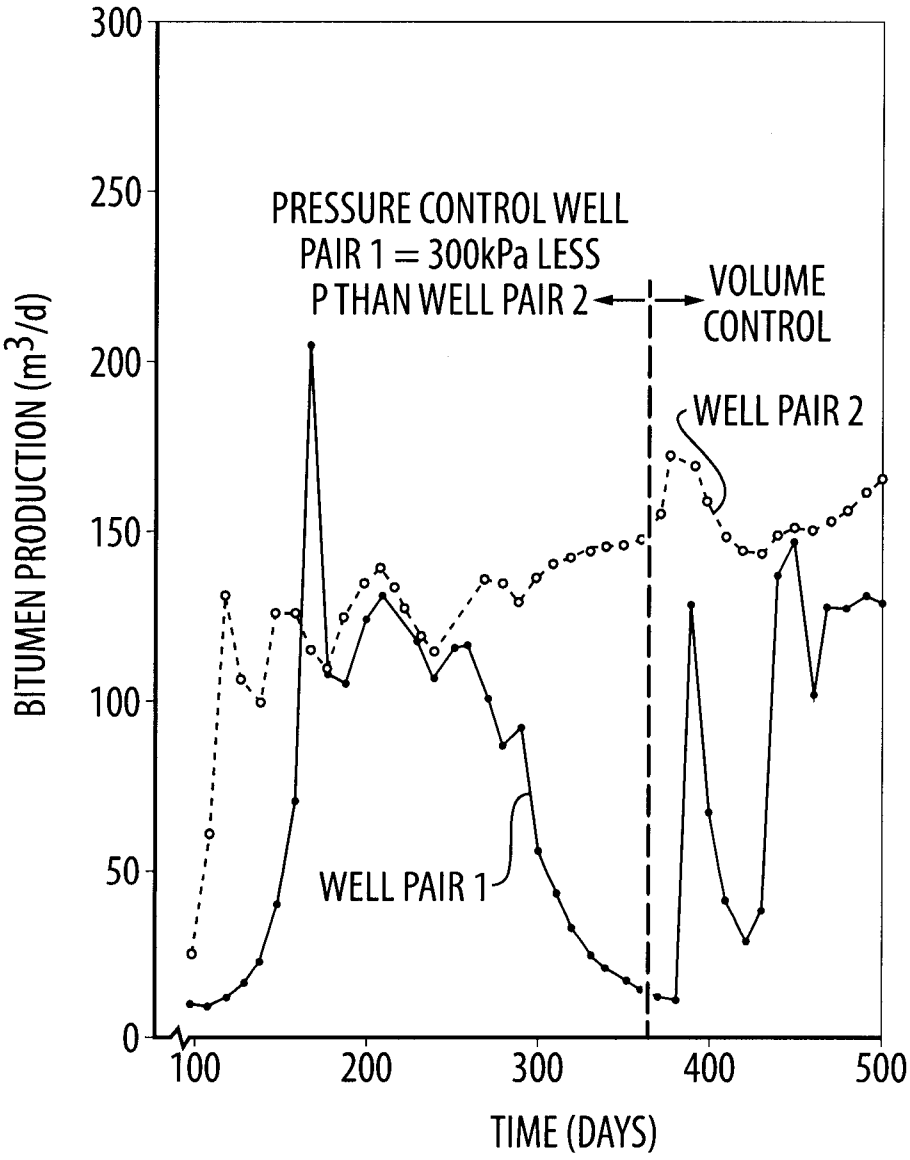

INDIVIDUAL WELL PAIR BITUMEN PRODUCTION (CASE 3)
BITUMEN PRODUCTION (m^3/d)
300
250
200
150
100
50
0
PRESSURE CONTROL WELL PAIR 1 = 300kPa LESS P THAN WELL PAIR 2
VOLUME CONTROL
WELL PAIR 2
WELL PAIR 1
100
200
300
400
500
TIME (DAYS)

FIG.23

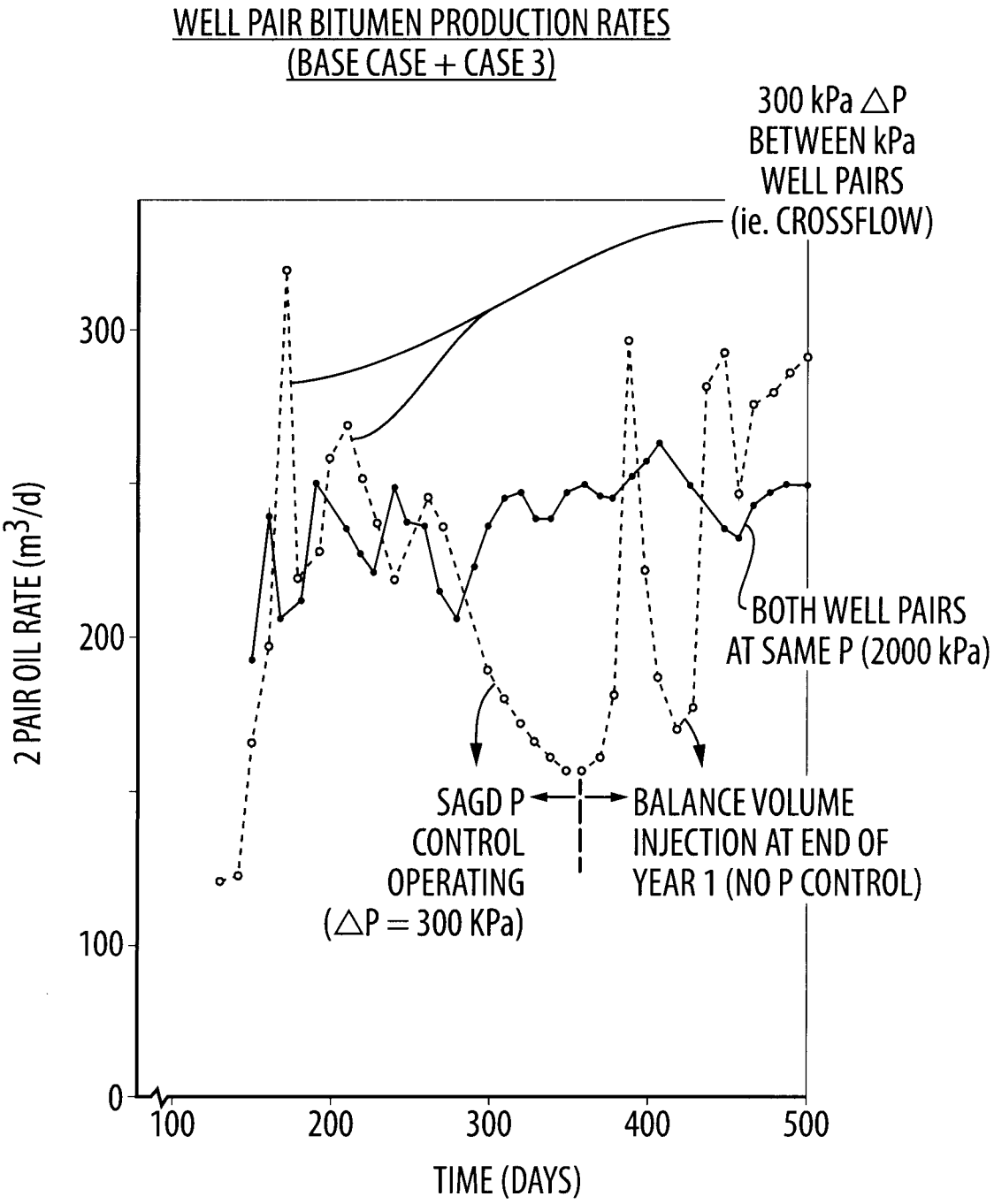

WELL PAIR BITUMEN PRODUCTION RATES
(BASE CASE + CASE 3)
300 kPa △P
BETWEEN kPa
WELL PAIRS
(ie. CROSSFLOW)
BOTH WELL PAIRS
AT SAME P (2000 kPa)
SAGD P
CONTROL
OPERATING
(△P = 300 KPa)
BALANCE VOLUME
INJECTION AT END OF
YEAR 1 (NO P CONTROL)
2 PAIR OIL RATE (m3/d)
TIME (DAYS)
0
100
200
300
400
500

FIG.24

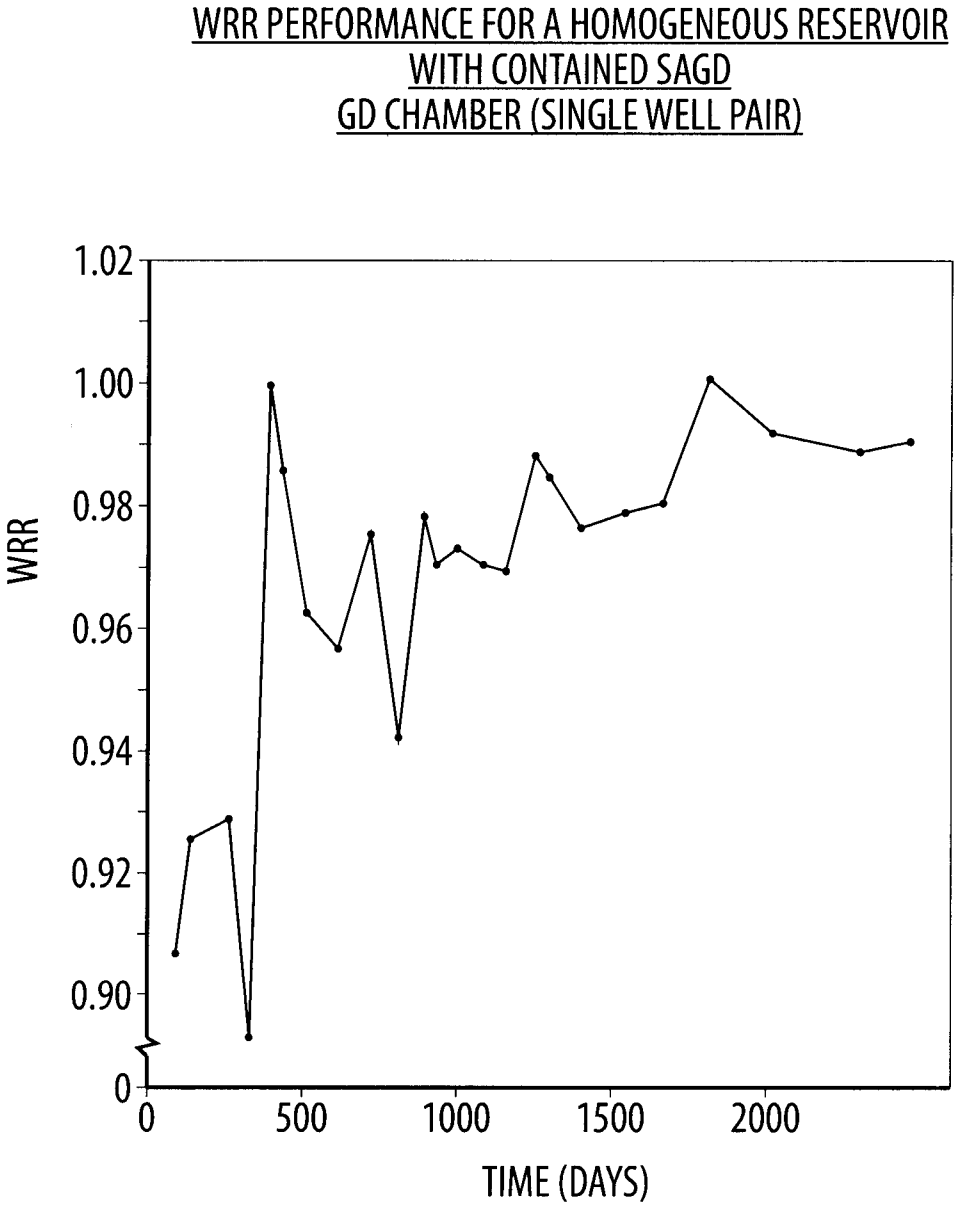

WRR PERFORMANCE FOR A HOMOGENEOUS RESERVOIR
WITH CONTAINED SAGD
GD CHAMBER (SINGLE WELL PAIR)
WRR
1.02
1.00
0.98
0.96
0.94
0.92
0.90
0
0
500
1000
1500
2000
TIME (DAYS)

FIG.25

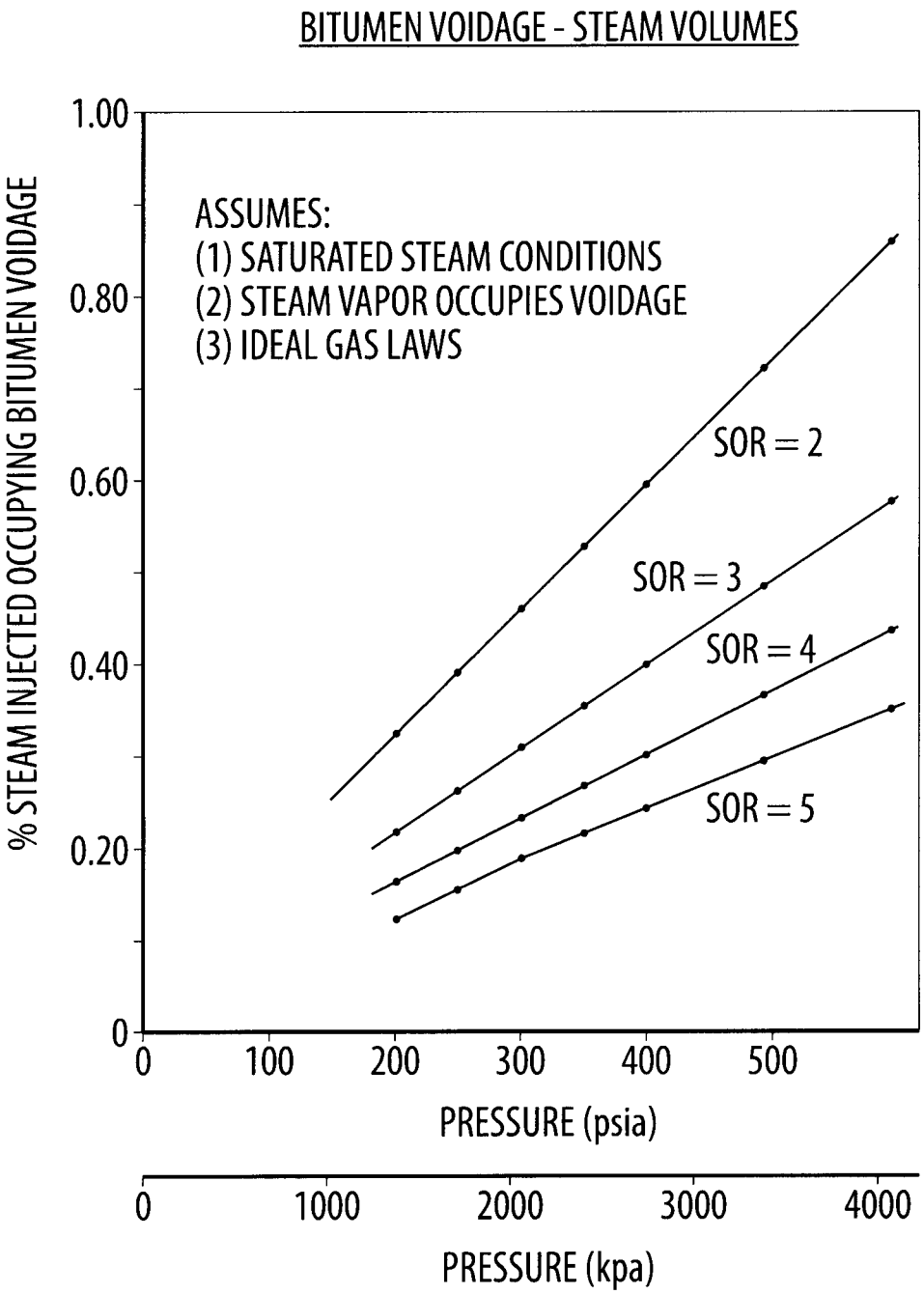

BITUMEN VOIDAGE - STEAM VOLUMES
% STEAM INJECTED OCCUPYING BITUMEN VOIDAGE
1.00
0.80
0.60
0.40
0.20
0
ASSUMES:
(1) SATURATED STEAM CONDITIONS
(2) STEAM VAPOR OCCUPIES VOIDAGE
(3) IDEAL GAS LAWS
SOR = 2
SOR = 3
SOR = 4
SOR = 5
0
100
200
300
400
500
PRESSURE (psia)
0
1000
2000
3000
4000
PRESSURE (kpa)

FIG.26

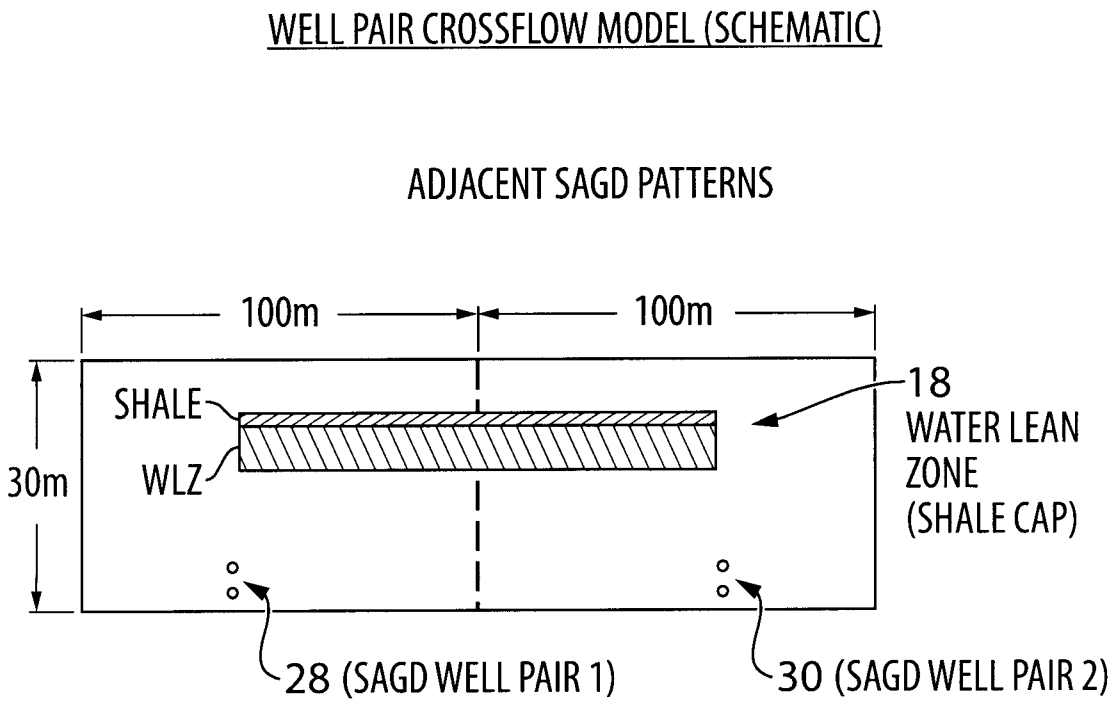
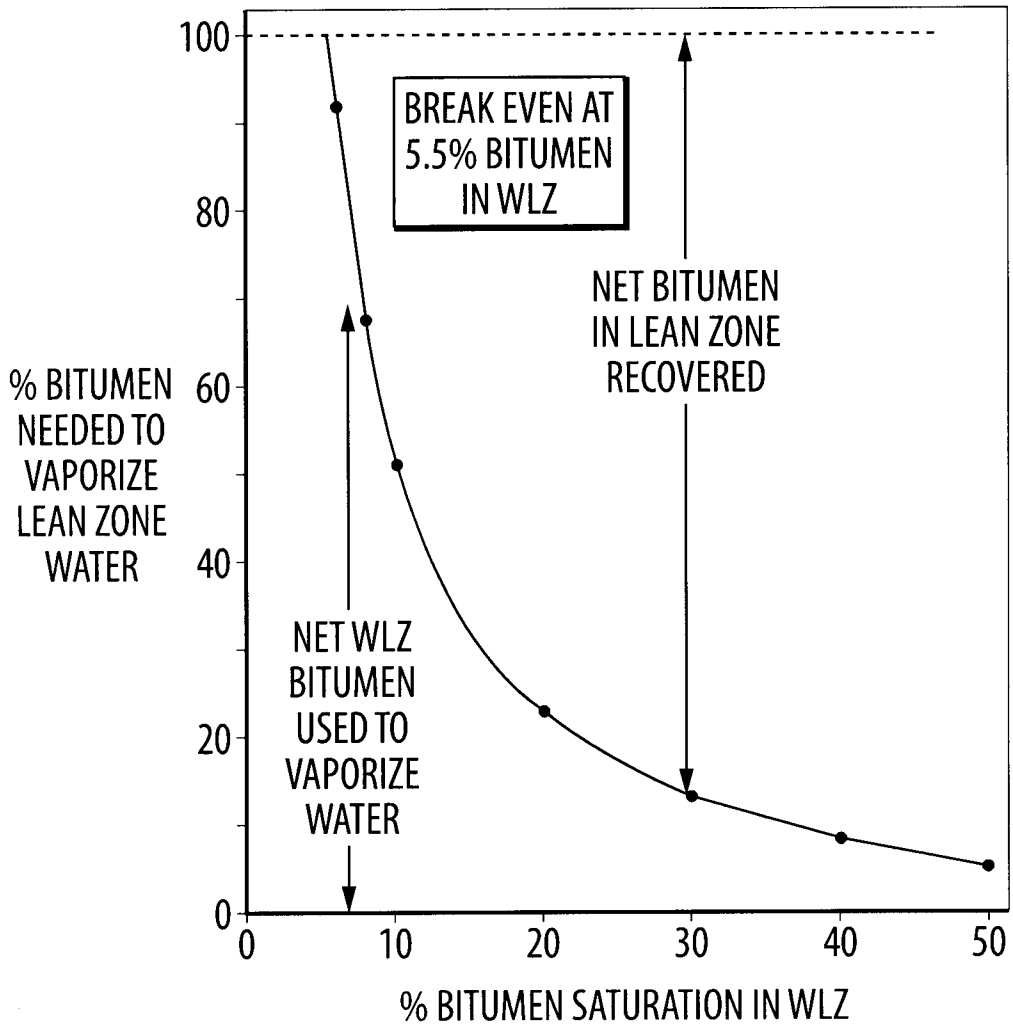

WELL PAIR CROSSFLOW MODEL (SCHEMATIC)
ADJACENT SAGD PATTERNS
100m
100m
30m
SHALE
WLZ
18
WATER LEAN ZONE (SHALE CAP)
28 (SAGD WELL PAIR 1)
30 (SAGD WELL PAIR 2)

FIG. 27



WATER LEAN ZONE (WLZ) BITUMEN RECOVERY

FIG.28

INTERNATIONAL SEARCH REPORT

International application No.
PCT/CA2013/000619

A. CLASSIFICATION OF SUBJECT MATTER

IPC: ***E21B 43/24*** (2006.01) , ***E21B 43/243*** (2006.01)

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC (2006.01): E21B 43/24, 43/243

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic database(s) consulted during the international search (name of database(s) and, where practicable, search terms used)

EPOQUE (Epodoc): steam, oxi+, oxy+, inject+, steam assisted gravity drainage, sagd

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2009/188667 A1 (LIM, G. et al.) 30 July 2009 (30-07-2009) *abstract; fig. 2; par. 74-84, 96-104*	1-12
A	WO 2006/074555 A1 (CHHINA, H. S. et al.) 20 July 2006 (20-07-2006) *abstract; claims; fig. 1*	1-12

[ ] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

* Special categories of cited documents :

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"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
26 September 2013 (26-09-2013)	30 September 2013 (30-09-2013)

Name and mailing address of the ISA/CA	Authorized officer
Canadian Intellectual Property Office Place du Portage I, C114 - 1st Floor, Box PCT 50 Victoria Street Gatineau, Quebec K1A 0C9 Facsimile No.: 001-819-953-2476	Christian Opris (819) 934-4264

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/CA2013/000619

Patent Document Cited in Search Report	Publication Date	Patent Family Member(s)	Publication Date
US2009188667A1	30 July 2009 (30-07-2009)	CA2650130A1	30 July 2009 (30-07-2009)
		CA2650130C	13 March 2012 (13-03-2012)
		US7740062B2	22 June 2010 (22-06-2010)
WO2006074555A1	20 July 2006 (20-07-2006)	CA2492306A1	13 July 2006 (13-07-2006)
		CA2594414A1	20 July 2006 (20-07-2006)
		CA2594414C	12 October 2010 (12-10-2010)
		US2008264635A1	30 October 2008 (30-10-2008)
		US7516789B2	14 April 2009 (14-04-2009)